PRINCIPLES OF DIRECT CURRENT ELECTRIC TRACTION

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A book for Tramway, Trolley-bus, and Railway Engineers and Personnel and all students of Electric Traction

BY

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PREFACE

In the past few years it has frequently been brought to the authors' notice that an up-to-date, reasonably small and compact volume dealing with direct current electric traction work was not available. As there seems to be a considerable demand for information on this subject, this book has been written for students of electric traction, for those employed in the manufacture of such equipment, for railway personnel, and for engineers and others interested. For the benefit of those not familiar with electrical subjects, several of the main ideas involved have been developed from first principles. In addition certain new ideas and schemes introduced in recent years have been included.

In the preparation of the manuscript the authors have received considerable assistance in the way of information and photographs from several companies. They therefore wish to acknowledge this assistance, and also the loan of photographs for reproduction in the text. The companies concerned are: The Metropolitan-Vickers Electrical Co. Ltd., The British Thomson-Houston Co. Ltd., The English Electric Co. Ltd., The Rheostatic Co. Ltd., The Consolidated Brake and Engineering Co. Ltd., The Vacuum Brake Co. Ltd., The Westinghouse Brake & Signal Co. Ltd., Bastian and Allen Ltd., Nife Batteries Ltd., Hadfields Ltd., British Insulated Cables Ltd., Sulzer Brothers (London) Ltd., The London and North Eastern Railway Co. Ltd., The Chief Mechanical and Electrical Engineer of the London Midland and Scottish Railway Co. Ltd., The London Passenger Transport Board, The Railway Gazette, The Institution of Electrical Engineers, The Associated Equipment Co. Ltd., Rotherham Corporation Transport, South Shields Corporation Transport, The Anti-Attrition Metal Co. Ltd. and The Swiss Locomotive and Machine Works.

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The authors also wish to acknowledge the considerable assistance rendered by their respective wives, without which the publication of this book would have been seriously delayed.

DOUGLAS W. HINDE
HERBERT E. INGHAM

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PRINCIPLES OF DIRECT CURRENT ELECTRIC TRACTION

Chapter 1

INTRODUCTION

In electric traction work several different applications of the fundamental principles exist; e.g., the tramcar and the trolley-bus both using the public highway, the former being railbound, and the latter steering controlled; and the electric train or locomotive which operates on a private track in common with normal railway practice.

The methods of supplying power to these various types of electric vehicle differ considerably.

THE TRAMCAR

The tramcar is supplied from *either* an overhead conductor consisting of a wire suspended above the track at intervals by brackets or wire stays carried on posts erected at the side or in the centre of the road. Current is collected by a trolley or bow collector, the return being made through the wheels and running rails; *or* from two insulated electrical conductors in the form of steel T rails, mounted thus ⊣⊢, laid below the surface of the road in the centre of each track, access being through a slot in the roadway, and current being collected by a "plough" attached to the underframe of the car. This is known as the "conduit" system.

THE TROLLEY VEHICLE

The trolley vehicle obtains its supply from two insulated overhead conductors along which run two independent trolleys mounted side by side on the roof of the vehicle, these trolleys being long enough to allow it to draw in to the kerb or cross over to the off-side of the road.

RAILWAY TRANSPORT

In railway transport, the method of supply depends on the operating voltage to be used. For low voltage systems (i.e. below 1000 volts), the conductor rail is used. This consists of a rail mounted adjacent to the running rails, power being collected by means of collector shoes mounted on the train, these being duplicated at each side of the train to allow for changes in the position of the conductor rail. Current return is usually made through the running rails, but in certain cases use is made of an insulated return rail mounted centrally on each track at the same height as the normal conductor rail. For higher voltages overhead wires are used, but due to the high speed of railway traffic and the heavy currents involved, special wire supporting arrangements have to be made, and a different form of collector gear employed, to ensure that there is no interruption in the supply due to the collector breaking contact with the wire. These are described in the chapter dealing with supply and collection.

SYSTEMS OF RAILWAY ELECTRIFICATION

Three distinct systems of electrification are in use at present:

(*a*) *Direct current*, the system dealt with in this book, and with one exception the only system in use in this country.

(*b*) *Alternating current*, both single and polyphase, used by many railways on the continent and in the U.S.A.

(*c*) *Composite systems*, in which motor generator sets on the locomotive or motor coach are supplied with alternating current. These sets generate direct current for the traction motors which are of the type described later in this book. Alternatively, the supply to the locomotive may be three-phase alternating current, and the traction motors single-phase, or vice versa.

Engineers differ in their opinions as to the best system, in this country direct current being now accepted as standard with a maximum pressure of 1500 volts, the two standard voltages being 1400 to 1500 with overhead collection and 600 to 650 with "third rail" collection. The possibility of employing a 3000 volt overhead system, however, has not been entirely ruled out.

OPERATING VOLTAGES

On direct current systems, operating voltages up to 3000 volts are in use in many parts of the world. Standard practice is to use third rail current collection on low voltage systems where the pressure is 600 volts, and overhead wires for higher voltages, the values of these being from 1,500 to 3,000 volts. Examples occur in practice which differ from this, e.g. the Manchester–Bury line of the L.M.S. is 1,200 volts third rail, and the new Southern Railway locomotive is fitted with a pantagraph for overhead collection at 600 volts for use when working in goods yards or at the dock side.

GENERATION AND DISTRIBUTION

Power supply is obtained in most cases by conversion from a high-tension alternating current supply at sub-stations spaced at intervals along the track, the spacing of these being economically governed by the line operating voltage and the type and density of the traffic on each section.

TECHNICAL ASPECTS

The merits of the modern tramcar are well known, viz. a large passenger carrying capacity, rapid acceleration and braking suitable for frequent stopping, and the feature of a track-bound vehicle being much easier to control under bad road and weather conditions.

The trolley-bus has the same passenger carrying and frequent stopping characteristics as the tramcar, but differs in that it requires no track of its own, can be brought up to the curb at stops, and steered around obstructions in its path.

These two arguments are advanced to demonstrate the advantages of the tramcar and the trolley-bus over the internal combustion-engined ominibus, but it is generally accepted that all three methods have their place in a large transport undertaking.

It is very rare for a new section of railway to be constructed as an electrified system and consequently most electrification schemes consist of the conversion of some or all of the traffic on an existing route to electric haulage.

The types of traffic which may be converted are as follows:

(*a*) Urban and suburban passenger traffic.
(*b*) Freight traffic only, this especially in difficult country.
(*c*) All classes of traffic, viz. express and suburban passenger and goods.

Before any system of electrification is decided upon, the traffic is reviewed to decide what proportion of electric haulage is to be used. On trunk lines where the whole of the traffic is to be converted, the initial cost of the apparatus may be considerable compared with that for steam haulage, however this is amply repaid by the increased availability in traffic and the higher climbing speed of the electric locomotive, together with the fact that if lengthy tunnels occur on the system, the loading or rate of passage of trains through such tunnels may be increased, as ventilation troubles incurred in removing smoke and fumes do not occur. This also applies with freight traffic, together with the fact that if the locomotives are arranged on the unit construction principle, several of these units may be operated together under the control of one driver, and hence the locomotive power supplied for any given train may be easily adjusted to that most suitable for the load to be hauled. The main argument against conversion to electric traction is that the modern steam locomotive, while not quite up to these standards, is already in existence, and in many cases the cost of conversion would consequently prove to be an uneconomical proposition. In countries where hydro-electric schemes may be employed to supply the power, and fuel supplies for steam traction have to be imported, conversion to electric traction frequently results in a large reduction of the operating costs.

FIG 1 —THREE-CAR TRAIN SET

(B T.H.)

The electrification of urban and suburban lines is a means of providing a faster service schedule over any given route, together with an increase in the possible traffic density due to the more rapid clearance of each section. An electric train of eight coaches, containing three or four motor-coaches, has a much higher rate of acceleration than the corresponding steam train, and consequently over short distances of approximately one mile between stations, the electric train reduces the time required by 25 per cent or more. For example, on a route of 11 miles with 7 intermediate stops the previous steam train took 34 minutes including stops, while the electric train which replaced it reduced this time to 27 minutes. This increased speed of operation enables a given frequency of trains to be maintained with less equipment. Another advantage is the ease with which the train size may be altered; an eight coach train can be made up from two four coach units and during quiet parts of the day, one of these units may be detached and left where it is readily accessible when the busy period again commences. As an alternative, three car units may be used, comprising a motor coach and two trailers, the rear trailer being fitted for driving when the train is travelling in such a direction as to cause this coach to be leading. These three-car sets may be used to build up trains of six, nine, and twelve coaches at peak traffic periods.

The following chapters outline the principles and constructional details of the various items of equipment used in direct current electric traction.

Chapter 2

TRACTION MOTORS

THE traction motor is essentially a means of converting electrical energy into rotational mechanical torque, the essential requirements being a magnetic field and an electrical conductor capable of motion in that flux or magnetic field.

GENERAL PRINCIPLES OF THE DIRECT CURRENT MOTOR

On passing a current along a conductor, concentric lines of magnetic flux are set up along its length, the direction of this flux being dependent on the direction of current flow, Fig. 2.

Considering this condition taking place in a steady magnetic field, the concentric lines of force are seen to act in the same direction as the main magnetic field on the right hand side, and in opposition on the left hand side, thus bending or distorting the magnetic lines of force round the conductor. Magnetic lines of force, being always in a state of tension, set up a mechanical force on the conductor, the direction of this force and its resultant motion being determined by the relative flow of conductor current and main magnetic lines of force. This function is illustrated in Fig. 3.

Taking a similar condition where no current flows in the conductor, but the conductor is moved in the magnetic field so as to cut the lines of force, an "electro-motive force" (e.m.f.) is set up between the ends of the conductor, and will cause a current to flow when connected to an external circuit. Assuming the same direction of conductor motion and main magnetic flux as that shown in Fig. 3, the current will flow in the opposite direction. In the first case electrical energy is converted into mechanical work, and in the second, work is converted into electrical energy, the displaced lines of force in the latter case due to generated conductor current, set up a retarding force in opposition to the applied force.

The preceding paragraphs briefly describe the principles involved when considering a "motoring" and "generating" direct current machine respectively. In practice, the main magnetic circuit consists of a steel yoke with inwardly projecting poles, the polarities of which are alternatively "North" (N) and "South" (S). A diagrammatic four-pole frame is shown in Fig. 4, the dotted lines indicating the paths of the main magnetic fluxes.

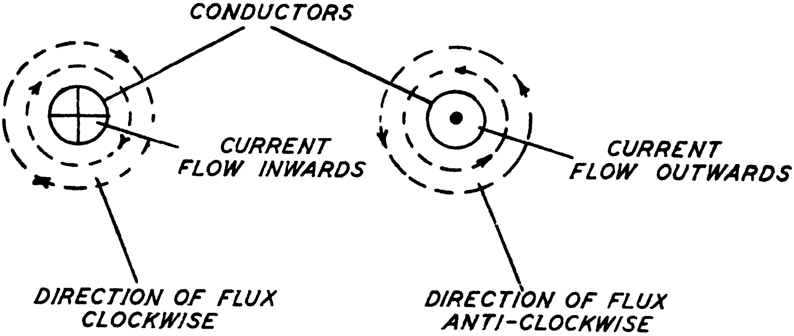


FIG. 2.—LINES OF FORCE AROUND A CONDUCTOR

The moving conductors are arranged in slots on the periphery of a cylindrical laminated steel core, and connected to a commutator which makes sliding contact with fixed brushes. Hence current is passed along the conductors in the appropriate direction as they enter the flux of the main poles. The whole rotating assembly is known as the "armature".

BACK E.M.F.

When motoring, as the armature rotates, the conductors cut the lines of force of the main field and hence have e.m.fs. produced in them which are in opposition to the supply current and to the applied voltage. It follows that the speed of the armature will adjust itself until the back e.m.f. is such that the resultant voltage between the applied and back e.m.f. is sufficient to pass the current necessary to meet the mechanical load and the efficiency losses in the motor itself.

ARMATURE REACTION

Armature Reaction is the effect on the flux distribution in the air gap between the poles and the armature, of the magnetic field produced by the current flowing in the armature conductors.

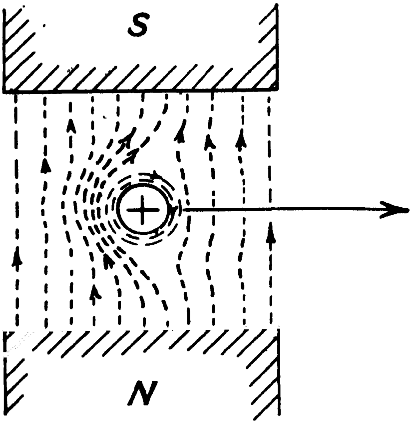


FIG. 3.—FORCE ACTING ON A CURRENT-CARRYING CONDUCTOR PLACED IN A MAGNETIC FIELD

Consider the case of a two-pole machine with its armature rotating in a clockwise direction, and with brushes placed so as to pass current to the conductors which lie in the mechanical or "geometric neutral axis" (G.N.A.), Fig. 5. All the conductors under the north pole carry currents whose directions are outwards, whilst currents in conductors under the south pole are inwards. This sequence of armature currents sets up a magnetic field whose axis coincides with that of the geometric neutral from left to right. Representing the two magnetic fields vectorially, OA. and OM. in Fig. 5, are main and armature fields respectively, and therefore OR. represents the resultant magnetomotive force, with the magnetic neutral axis perpendicular to it and denoted M.N.A. On no-load when the armature current is very small and armature flux negligible, the magnetic neutral and geometric neutral axes are approximately coincident. The effect of armature reaction is to move the magnetic neutral axis round in a direction opposite to the armature rotation, and obviously the angle of movement is dependent on the value of armature current or load. In effect, this action ultimately causes a strengthening of the flux on the leading pole tips, and a weakening effect on the trailing pole tips. Fig. 6 shows flux distribution in the air gap under the poles on no-load and full-load, with the distortion due to the armature field on full-load.

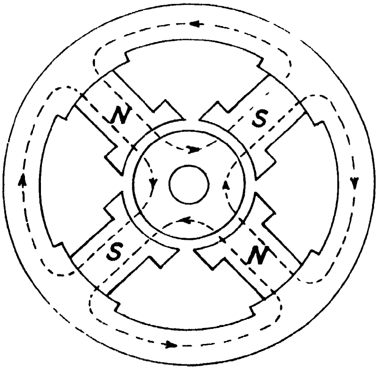


FIG. 4.—FOUR-POLE MAGNET FRAME

It will be appreciated that

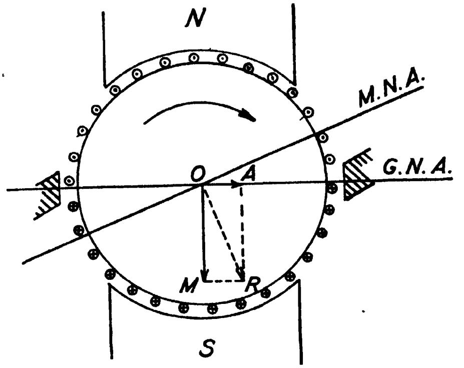


FIG. 5.—DIAGRAM ILLUSTRATING THE EFFECT OF ARMATURE REACTION

armature reaction has an effect on the characteristics of a direct-current machine, unless steps are taken in the design to counter its effect. This may be done by using specially shaped pole shoes, or by arranging for compensating windings to be fitted in the pole shoes and connected in series with the armature. These steps, of course, are not essential unless these particular characteristics of the motor are undesirable.

BRUSH POSITION

The position of the armature field is directly linked with that of the brushes. Where machines necessarily have to operate with a similar speed characteristic in either clockwise or counter-clockwise rotation, it is usual to set the brush position on the geometric neutral axis, but with a uni-directional machine, the

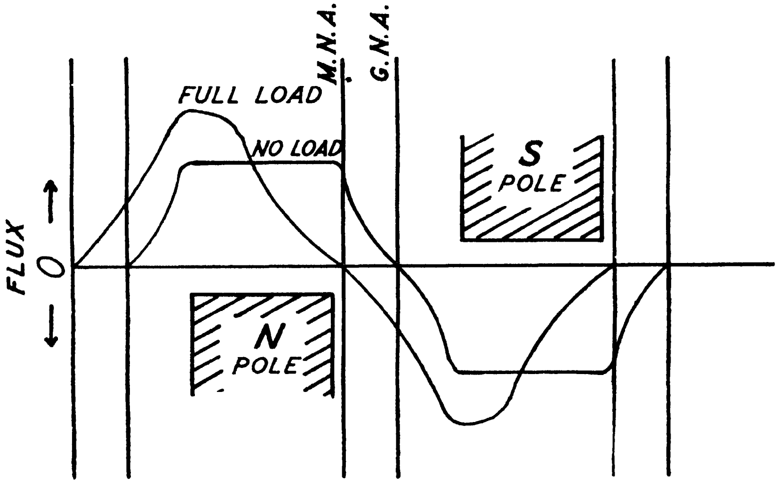


FIG. 6.—DISTORTION OF MAIN FIELD FLUX DUE TO ARMATURE REACTION

brush position may be adjusted to lessen the distorting effect of the armature reaction.

COMMUTATION AND COMMUTATING POLES

When a brush spans two adjacent commutator segments, the section of the armature winding connected between them becomes short circuited, the term "commutation" denoting the changes that occur to the current during this short-circuit period. The commutating cycle is demonstrated in Fig. 7.

(*a*) Coil "2" is about to be short circuited by the brush and is carrying half the current passing between the armature and the brush in a direction as indicated by the arrows.

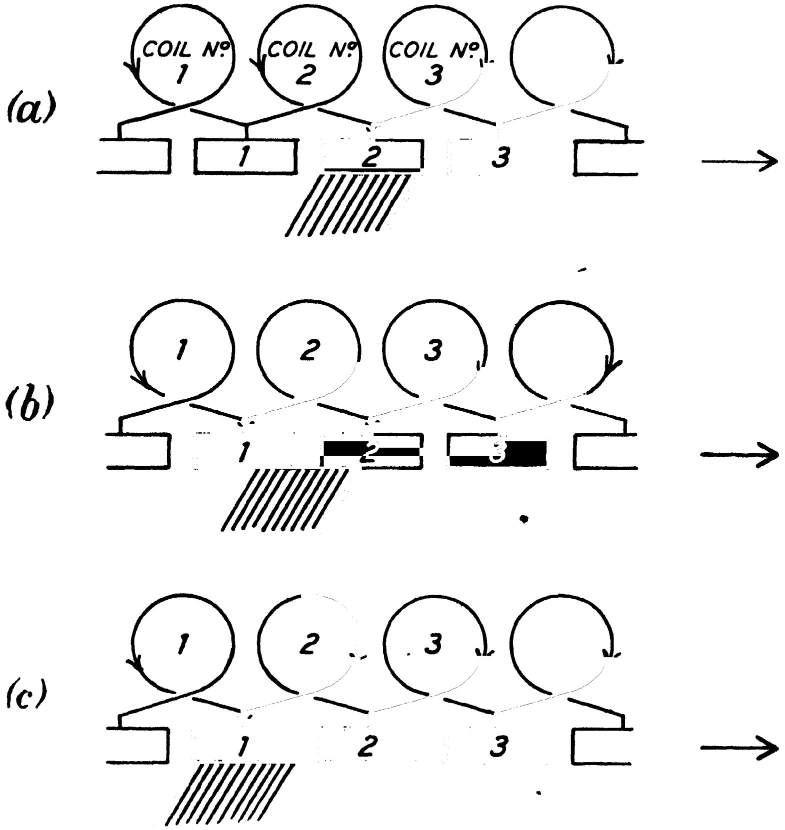


FIG. 7.—THE COMMUTATING CYCLE

(*b*) At this instant during the rotation the coil is under short circuit and does not carry any of the brush current.

(*c*) The coil "2" is now clear of the short circuit and is again carrying half of the brush current, but current now flows in the opposite direction, hence a complete reversal of current has occurred in that coil.

From this it is obviously desirable that the current should be reduced to zero and brought up to its previous value, but in the reverse sense, during the momentary short-circuit period. Any difference in the current flowing in coils "2" and "3" must travel from commutator segment "2" to the brush in the form of an arc, ultimately causing severe burning of the commutator and the brushes, whilst increasing the risk of complete arcing between brushes of opposite potential.

Since a very high rate of change of current is necessary to complete the commutating cycle, a back e.m.f. is set up in the coil by self-induction which opposes the reversal of current. This back e.m.f. is generally spoken of as the "Reactance Voltage".

In modern machines this voltage is effectively suppressed by the use of auxiliary poles producing a commutating field. These poles are fitted in the magnetic yoke, or frame as it is most often termed, midway between the main poles, and hence have more generally been termed "interpoles". The interpole polarity in the case of a motor must be the same as the main pole behind it in the direction of rotation. Since the commutating field required must be proportional to the armature current, the interpoles are connected in series with it, and therefore the field strength is automatically adjusted to the value necessary at any instant.

CHARACTERISTICS OF DIRECT-CURRENT MOTORS

There are three methods of producing the main field excitation of a direct-current motor, viz. shunt, series and compound methods, the characteristics of the machine being determined by the method adopted.

SHUNT MOTOR

Excitation is provided by means of field coils with a relatively large number of turns and a high resistance, wound on each main pole and "shunted" or connected across the supply terminals. The flux per pole produced depends on the coil current and the magnetisation characteristic of the iron used for the frame and pole pieces. A typical magnetisation curve of material suitable for motor frames is shown in Fig. 8, and it will be seen that the flux is approximately proportional to the excitation at the lower values, but the increase of flux per ampere-turn decreases as the saturation of the magnetic circuit is approached, this point occurring where no change of flux is obtained with further increase of excitation. In order to maintain reasonable running stability it is usual to work at a point slightly over the bend of the magnetisation curve, where armature reaction and small variations in excitation do not appreciably affect the value of the main flux.

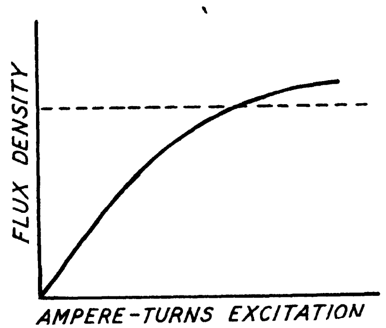


FIG. 8.—MAGNETISATION CURVE OF SHUNT MOTOR

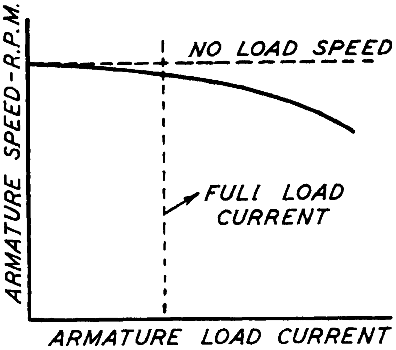


FIG. 9.—SPEED-LOAD CURVE OF SHUNT MOTOR

Fig. 9 shows a typical speed-load characteristic curve of a shunt excited motor. The slight droop of the curve from no-load to full-load is mainly due to the increasing armature resistance drop, determined by the product of armature current and resistance. Subtraction of the armature resistance drop at full-load and no-load from the applied voltage, shows the back e.m.f. to be generated in the armature at the full-load point to be less than that at no-load, and therefore a corresponding fall in speed will occur to counteract this difference. As this speed reduction of a shunt motor is in the order of 5 per cent, the machine is generally considered to be a constant speed motor.

The speed of a shunt motor may be varied however, if desired, by weakening or strengthening the main field flux. This is most easily accomplished by inserting a variable resistance in series with the shunt field. When the field flux is reduced the armature back e.m.f. is likewise reduced and the armature current increases correspondingly, which in turn increases the armature speed to a point where the total of back e.m.f. and armature resistance drop again reaches a value equal to the line voltage. Similarly, a speed reduction is obtained with an increased field strength.

SERIES MOTOR

The term "series motor" is derived from the fact that the field coils are in series with the armature, and carry the armature current; they are wound with a relatively small number of turns of heavy section copper wire or copper strip. The field flux varies with the motor current, and since the speed is inversely proportional to the flux, the series motor is essentially a variable speed machine, the speed being low on heavy load and very high on light loads. A typical speed-load characteristic curve of a series motor is shown in Fig. 10. From the current-flux curve it will be seen that the working range of flux is well below the saturation value, and providing that this condition is observed, the torque exerted by the armature is proportional to the square of the current, consequently the starting torque is very high.

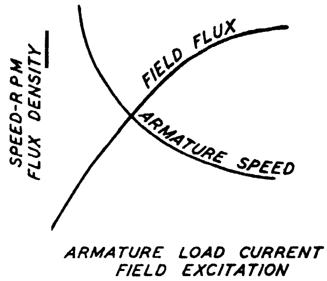


FIG. 10.—SPEED-LOAD AND FLUX CURVES OF SERIES MOTOR

The series motor is obviously the ideal type of machine for traction purposes, where heavy masses have to be accelerated from rest and operated at relatively high speeds. As a very light load condition does not exist in traction applications on account of the increasing train resistance as the speed rises, it is often necessary to modify the field windings if both the high starting torque feature and a fast running speed be required. The method adopted is that of providing additional series field turns and bringing out tappings, so that one or more sections may be cut out whilst running, to obtain the higher speeds. Connections for such a motor and corresponding speed-load characteristic curves are shown in Figs. 11*a* and 11*b*.

Before passing on to the principles required in traction working, it would be well to note the third type of machine known as the compound motor.

COMPOUND MOTOR

This motor has its field poles wound with both shunt and series coils, and by suitable design almost any shape of speed characteristic may be obtained to suit the application. Usually the two field windings are connected so as to give accumulative compounding, i.e. so that the ampere turns of each winding produce flux in the same direction. This method has several advantages, including load stability and protection against overload, in that as the load on the motor increases, the corresponding increase of current in the series field coils produces more main field flux. This automatically reduces the armature speed, hence the ultimate output becomes limited. In the case of a compound traction motor, the high starting torque of the series motor together with limited maximum speed characteristics are obtained.

The compound motor also runs quite stably as a generator, in which case it automatically becomes a decompounding generator with the reversal of armature and series field current. This feature is useful when applied to traction work for the purpose of regenerative and rheostatic braking.

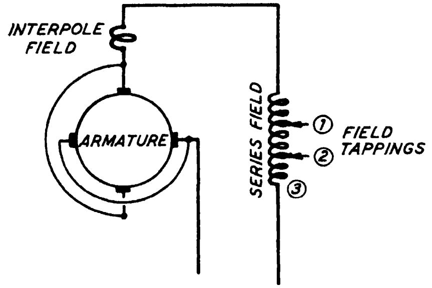


FIG. 11a.—TAPPED FIELD SERIES MOTOR CONNECTIONS

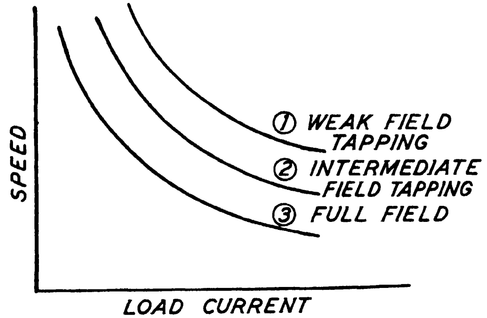


FIG. 11b.—TAPPED FIELD SERIES MOTOR CHARACTERISTICS

EXCITATION OF DIRECT-CURRENT GENERATORS

Since "motoring" and "generating" of a direct-current machine are merely a reversal of function, the same three excitation methods apply as described for motors.

Strictly speaking a generator is a source of electrical energy, and must, therefore, provide its own excitation current, otherwise it must be separately excited from some external supply.

SELF-EXCITED SHUNT GENERATOR

Steel, as used for direct-current machine construction, has the property of retaining a small amount of magnetic flux when excitation has once been applied; this property is termed "hysteresis" and makes spontaneous self excitation possible. When the generator armature is rotated in its field system, a small e.m.f. is produced by this residual magnetism of the main poles, which, when applied to the shunt field coils, produces a small excitation current. Providing that the shunt field coils are connected to the armature in the correct relative sense, a building up process will commence and continue to a point determined by the frame magnetisation characteristic and the shunt field resistance. A field magnetisation curve of a direct-current machine is shown in Fig. 12, on which is also plotted the shunt field resistance line, the latter being obtained from "Ohm's Law".

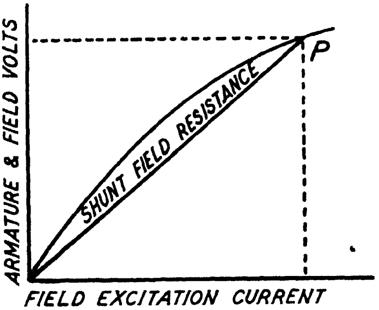


FIG. 12.—MAGNETISATION CURVE OF SHUNT-EXCITED GENERATOR

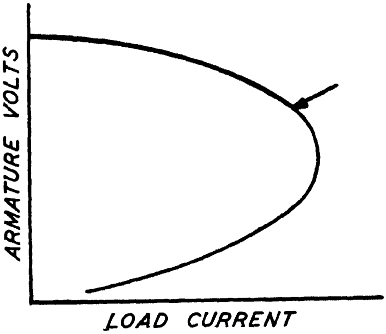


FIG. 13.—LOAD CHARACTERISTIC OF SELF-EXCITED SHUNT GENERATOR
(Note rapid decrease in stability beyond arrow head)

The point of intersection of the two curves "P" represents the maximum value to which the field current will build up, due to the fact that any higher field current than that corresponding to this point requires a greater voltage than is produced by the corresponding flux. The maximum shunt field resistance with which a generator will tend to build up on no-load is often termed the "critical resistance", and therefore a self-excited generator will self excite only when the field resistance is less than the critical value.

A separately excited machine, of course, is independent of the field winding resistance, maximum generated voltage being limited by flux saturation only.

Figs. 13 and 14 show volts-current characteristics of self and separately excited shunt generators.

Individual characteristics may be varied to suit the application, the actual shape being determined by the degree of flux saturation at the normal working voltage.

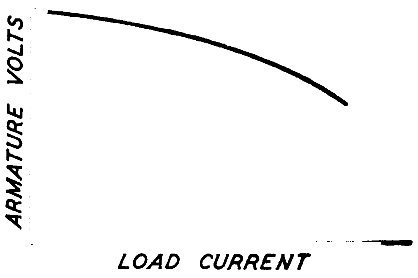


FIG. 14.—LOAD CHARACTERISTIC—SEPARATELY EXCITED SHUNT GENERATOR

SERIES GENERATOR

As the term suggests, the field winding and armature of this type of machine are in series carrying the same current and this fact determines the nature of the characteristic, as shown in Fig. 15. With the correct relative connection between field and armature, due to the residual magnetism the machine builds up on being connected to an external load resistance.

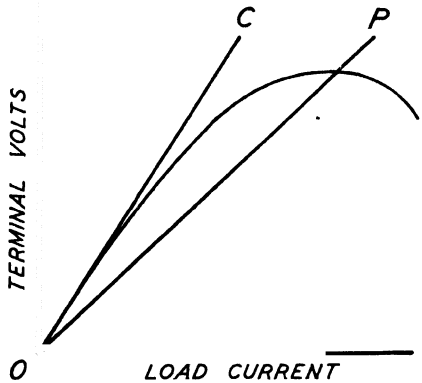


FIG. 15.—LOAD CHARACTERISTIC OF SERIES GENERATOR

The line "OP." in Fig. 15 represents the resistance of the external circuit. A line "OC." drawn tangentially to the characteristic curve represents the critical external resistance since it is the maximum value with which the generator will tend to build up.

Now suppose an externally driven series motor is short circuited through a resistance, the residual magnetism left by the previous motoring current will produce a small armature voltage and likewise a current in opposition to the normal flow of current, which when passed through the series field, will produce ampere-turns destroying the residual magnetism. Therefore, the conditions for a series motor to operate as a generator only occur when either the field connections or the armature rotation have been reversed. This fact is taken into consideration when using series motors for rheostatic braking on traction equipment.

COMPOUND GENERATOR

This is normally a shunt excited machine with series turns carrying the armature current so as to produce excitation ampere-turns de-compounding those of the shunt winding. Such a machine may be designed to give almost any type of characteristic, the actual slope of the characteristic curve being governed by the ratio of the shunt ampere-turns to the series ampere-turns.

Where a shunt or compound generator is working in parallel with a fixed supply source, the armature and shunt field voltage is stabilised, and the value of the current generated may be varied by field regulation or by armature speed.

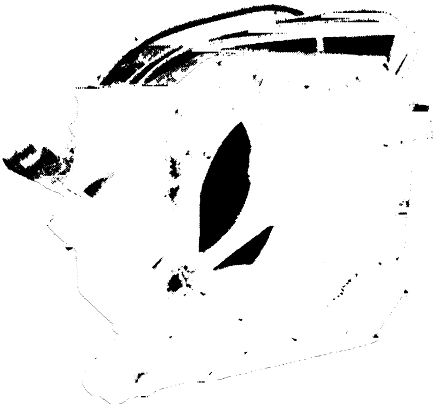


FIG. 16a.—RAILWAY MOTOR FRAME

(*Metro-Vickers*)

THE DIRECT CURRENT TRACTION MOTOR

The direct current traction motor is essentially some form of series motor, due to its high starting torque and variable speed characteristic. It differs in construction from the normal commercial type machine in that it must be very robust, capable of withstanding severe mechanical shock and vibration, and must have a high overload capacity. The ventilation system requires careful design, in order to avoid surfaces which will accumulate dirt and grit picked up from the track or road.

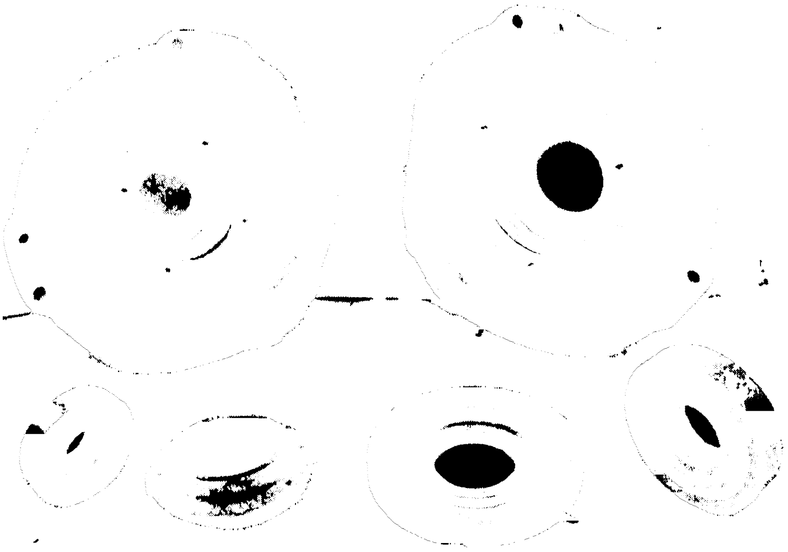


FIG. 16b.—TRAMWAY MOTOR END-HOUSINGS AND BEARINGS (*Metro-Vickers*)

CONSTRUCTIONAL DETAILS

In order to explain fully the construction of the Direct Current Traction Motor, the various component parts are described in detail, commencing with the field frame.

THE FIELD FRAME

This is of cast steel and is usually of the box cast type, with an opening at each end bored and recessed to accommodate the armature bearing housings, which are secured into the frame by steel bolts screwed into it. Suitably machined seatings are provided for the main and inter-poles. Openings as large as possible are also provided at one end of the frame for easy inspection of the commutator and brushgear, these openings being fitted with detachable steel covers, fabricated from sheet metal. Fig. 16 shows a typical railway traction motor frame and a pair of roller bearing end-housings for tramway motors. In cases where brushgear is only fitted on the upper surface of the commutator, one inspection cover only suffices, the lower section of the frame being cast solid.

The method of motor suspension or mounting varies of course with the class of equipment. Tramway motors are almost universally axle mounted whether for single or double bogie type vehicles. The axleway is cast with the frame body and fitted with split sleeve bearings with detachable axle-caps. Fig. 17 shows a tramway motor complete with its axle bearing details.

Railway type motors for motor-coach stock are usually nose suspended and axle mounted as with the tramway equipments. Locomotive motors may be either axle mounted, as for motor-coach stock, or where larger machines of over 400 horse-power are employed, they are carried on the locomotive frames, in which case a special method of drive becomes necessary. The limiting factors governing the choice of mounting are gauge of track, maximum speed, and rated motor output required.

Trolley-bus motor frames have a somewhat different physique, being chassis mounted and cast with lugs at each side for this purpose. On modern machines where weight is a controlling factor, the tendency is to use bearing end-housings of cast light alloy. The trolley-bus motor frame has a symmetrical cross-section and the thickness of metal is cut down to a minimum where possible, but thickened up in the parts carrying the maximum flux density. Fig. 18 gives a diagrammatic illustration of a

FIG. 17.—COMPLETE TRAMWAY MOTOR

(B.T.H.)

trolley-bus frame, with sections thickened up to carry both main and interpole fluxes, the flux paths being indicated by dotted-lines.

THE ARMATURE CORE

The armature core is built up of thin steel laminations, each lamination being thinly coated with insulating material to cut down eddy current losses to a minimum. Axial core ducts are provided to allow a free passage of air through the core for cooling purposes. The core is carried on and keyed to a steel spider being held in position by a steel end-plate and locking nut. From experience it has been found that moisture and dust tend to penetrate into the overhanging sections of the armature windings, and special sealing plates are fitted at each end of the core to avoid this action. The spider, which is pressed on to the shaft, supports the winding overhang at the back-end and also extends through the commutator hub, thus enabling the shaft to be removed or replaced without disturbing the armature winding or the commutator. Figs. 19 and 20 show longitudinal section of armature and unwound armature with commutator fitted respectively.

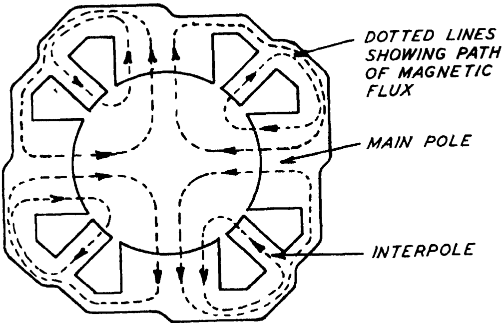


FIG. 18.—LIGHTWEIGHT MOTOR FRAME SECTION
(Note increased thickness where it is required to carry both main and interpole fluxes).

THE COMMUTATOR

The commutator is built on a separate steel hub carried on and keyed to the extension of the armature spider, being locked in position by a ring-nut. The commutator bars of hard drawn copper are insulated from each other with pure mica. Three methods are employed for holding the commutator bar assembly

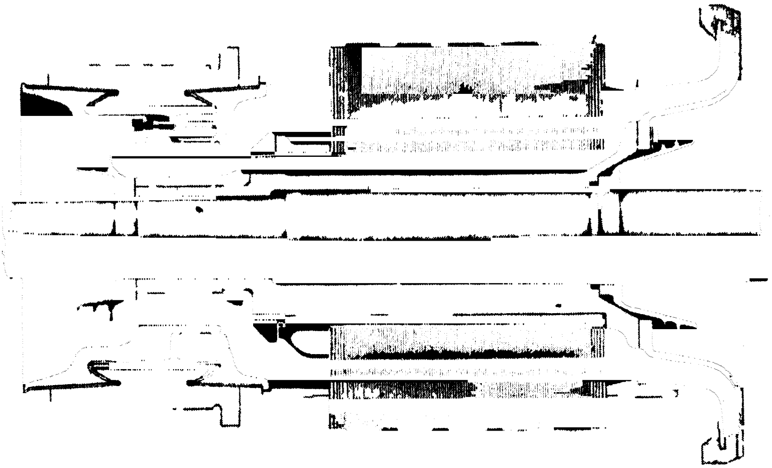


FIG 19 —SECTION THROUGH ARMATURE CORE

(*Metro Vickers*)

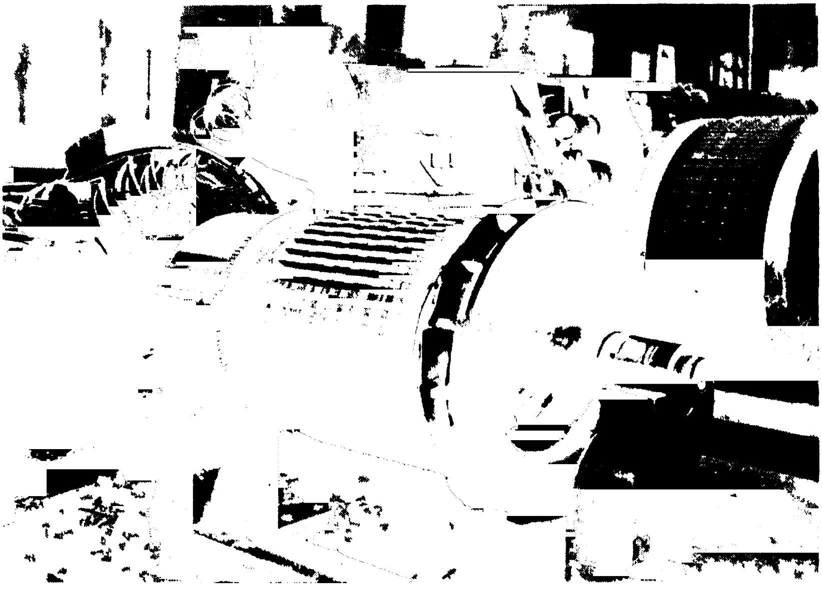


FIG 20 — UNWOUND ARMATURE WITH COMMUTATOR

(*Metro-Vickers*)

in a cylindrical form, against distortion from stresses set up by centrifugal action and temperature changes. These methods are as follows:—

(*a*) *The Wedgebound Method.* The copper bars are machined to the shape as shown in Fig. 21, and the whole copper-bar and mica assembly is secured in position by steel end-flanges fitting deeply into the "vee" notches. These end-flanges are insulated from the copper bars by moulded micanite end-rings and the whole clamped together by steel bolts.

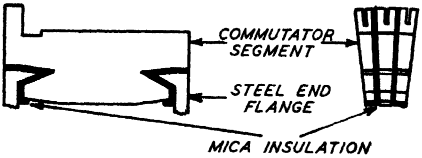


FIG. 21.—WEDGEBOUND COMMUTATOR

The name "Wedge-bound" is derived from the fact that the commutator bars are held radially by the pressure on the wedge faces of the bars and end-rings.

(*b*) *Archbound Method.* This construction is very similar to that of the previous method but in this case the angle on the upper face of the vee-ring is a few degrees less than that of the vee-notch in the copper segments. The retaining pressure consequently becomes radial and between the commutator bars, thereby rigidly holding the whole assembly (Fig. 22).

(*c*) *The "Shrink-ring" method* is applied in cases where exceptionally high peripheral speeds are required, and is rarely used for traction machinery. The commutator is built up in the normal way with vee end-rings, but in addition has rings of high tensile steel shrunk on to it externally, layers of pure mica having been built up solidly as insulation between the shrink-rings and the commutator surface. The amount of shrinkage of the rings is so designed that the rings are pre-stressed to a value above that produced by the maximum centrifugal force, thereby ensuring absolute rigidity.

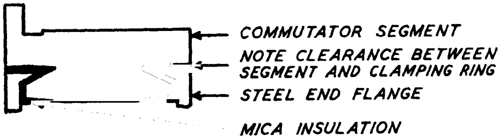


FIG. 22.—ARCHBOUND COMMUTATOR

ARMATURE WINDINGS

In modern direct current machinery, all armature windings are of the "Lap" or "Wave" types or some modifications of these.

Wave Windings. For standard series traction motors the simple wave winding is normally adopted. Fig. 23 shows the developed diagram of a simplified single turn wave winding. Single turn coils are always used where possible, but as the working voltages involved are normally high (e.g. 500 to 1,500 volts), more than two conductors per slot are necessary to avoid making the number of slots so great as to be impracticable. Armature windings are arranged in two layers, each slot carrying two coil sides, one in the lower and one in the upper portion of the slot. Up to sixteen conductors may be placed in a slot, i.e. eight in each of the upper and lower layers, these being taped separately as composite coils. As each of the conductors is insulated independently, the coils still remain single turn.

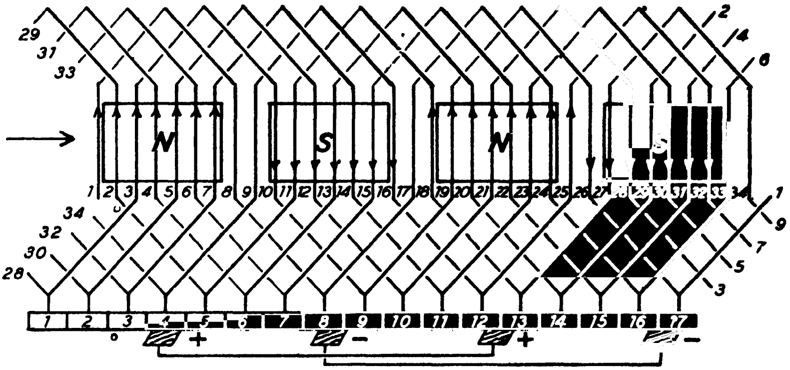


FIG. 23.—DEVELOPED DIAGRAM—SIMPLE WAVE WINDING

For simplicity the circuit in Fig. 23 has only one conductor per coil, each of which may be regarded as a winding element, the whole winding consisting of a series of these elements connected between consecutive commutator segments. Suitable coil pitches are used to include all the conductors in the winding, the sequence of end connections being either progressive or retrospective. The coil or slot pitches, referring to the back and front spans may be denoted as Sf and Sb and are approximately equal to the pitch of a pair of adjacent poles. After passing through the number of winding elements equal to the number of pairs of poles, the winding should return to a point, either two conductors in front or two conductors behind the starting point, according to whether the winding is to be progressive or retrospective.

For this reason, the mean of the front and back slot pitches (Sm) is equal to the total number of conductors (N) plus or minus two, all divided by twice the number of pole pairs (p), i.e.

$$\mathrm{Sm} = \frac{\mathrm{Sf} \pm \mathrm{Sb}}{2} = \frac{\mathrm{N} \pm 2}{2\mathrm{p}}$$

Any even number of conductors cannot necessarily be adopted, as the mean pitch must be a whole number. For example, assuming 36 conductors the mean pitch would be 8½ or 9½, which is unsuitable. In the case of 34 conductors the mean pitch would be 8 or 9 and taking eight as a suitable figure the winding data would then be:

Number of conductors	34	Front slot pitch	9
Pole pitch	8½	Back slot pitch	7

assuming one conductor per slot.

As there are only two parallel circuits through a wave winding, one pair of brush arms is sufficient, these being placed in the most accessible position for carrying out inspection and maintenance. Because all the armature coils in the two circuits are in series between the brushes, the effect of unbalanced field flux distribution is minimised, so that the magnetic section of the motor frame may be reduced to a somewhat unsymmetrical form in order to accommodate the main driving axleway, a form of frame which is quite common on the small types of traction motor. It is found necessary in designing some machines to keep the axial length of the commutator as short as possible where space is limited, and therefore more than a single pair of brush arms must be used in order to carry the armature current without exceeding the normal brush current density. In such a case brushes of like polarity are looped together, the effect being that of short circuiting one loop of the winding between the two brushes, and therefore, whether two or more brush arms are used, the number of parallel circuits in the winding remains two.

Lap Windings. Fig. 24 shows the different method of connections required for a lap winding. Again taking the case of a four-pole machine, suppose the total number of conductors is 32. This gives the following winding data:

Number of conductors	32	Front slot pitch	9
Pole pitch	8	Back slot pitch	7

With the lap type of winding the number of parallel circuits is the same as the number of poles so that for a machine with four poles the armature coil current in a lap winding is half that

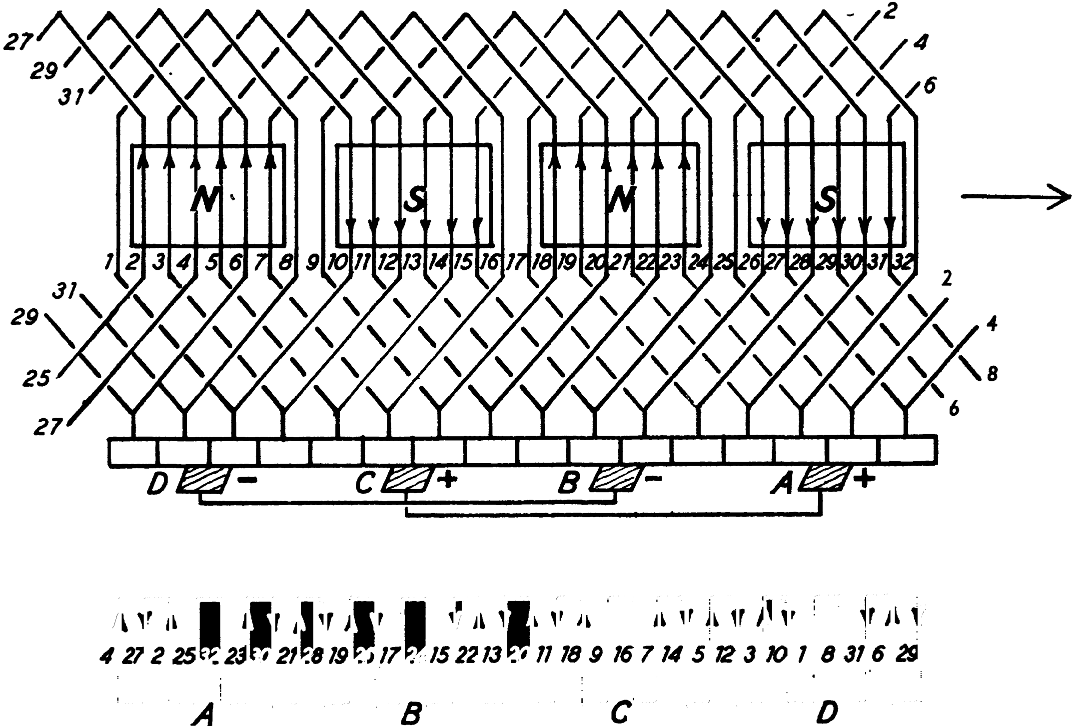


FIG. 24.—DEVELOPED DIAGRAM—SIMPLE LAP WINDING AND EQUIVALENT RING CIRCUIT

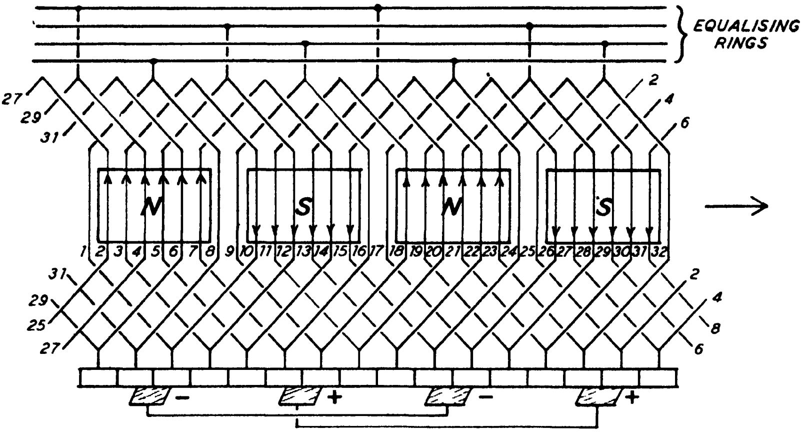


FIG. 25.—DEVELOPED DIAGRAM OF SIMPLE LAP WINDING WITH EQUALISING CONNECTIONS

in the equivalent wave winding. This fact assists in the commutation, since the rate of reversal of current, and consequently the reactance voltage produced, is proportional to the current in the coil. In high speed heavy current motors therefore, the lap type of winding is most desirable. The main disadvantage of a lap winding is the necessity for equaliser connections which are made with equalising rings situated at the back end of the armature winding. These consequently increase the overall length of the armature and, in comparison with the wave wound type, this results in additional size and cost for an equivalent horse-power output. Another disadvantage is that the number of brush arms required is equal to the number of poles, which may present difficulties in accommodation and accessibility if space is limited.

In a lap winding, the parallel circuits consist of conductors under the action of two adjacent poles only. Since it is not practicable to obtain identical field strengths from each pole, induced e.m.fs. in the various coils are not equal. Such out of balance will cause heavy circulating currents to flow through closed sections of the winding even for light loads, which, when imposed on the load current, would cause excess heating of the armature and also interfere with commutation. For this reason, points in the winding which, at any instant during rotation, are in the same position relative to their respective poles, are connected to short-circuiting rings which carry any out of balance current that arises. Fig. 25 shows a lap winding circuit with equaliser connections.

ARMATURE COILS

Armature coils are of formed copper strip, the cross-sectional area depending on the coil current of the armature. After annealing and being formed to the correct shape to suit the armature core and commutator pitches, each conductor is insulated over its entire length with mica tape. The appropriate number of conductors comprising one coil are grouped together and preliminarily bakelised, again wrapped with mica tape over the slot portion, and finally the composite coil is insulated with asbestos tape, bakelised, and hot pressed over the slot portion so as to form a shape fitting exactly to the dimensions of the core slot. This method is in accordance with the B.E.S.A. insulation specification class "B".

With the development of glass fabric as an insulating material in recent years, glass tape has come to be adopted for traction work in place of asbestos and cotton tapes, as it is more robust, non-hygroscopic and heat resisting.

Fig. 26 shows a formed armature coil insulated ready for use.

The operation of fitting the formed coils into the core slots and connecting the conductor ends to their respective commutator "riser" lugs is referred to generally as armature winding. Each slot carries two coil limbs, the winding pitch being either progressive or retrospective, so that each coil has one side in the lower half of a slot, and the other side in the upper half of a slot, the position of which is determined by the winding pitch. After all coils are fitted into position the core slots are sealed over with insulating packing strips. The coil sections which overhang the ends of the armature core are supported by and insulated from the armature spider at the back-end, insulated on the upper side at both ends with mica and protected by a layer of glass fabric or suitable webbing. The completely wound armature is held solidly by a series of steel wire bands, placed at points along the whole length of the armature. This banding wire is of special high tensile steel, each band consisting of several turns of wire, held and soldered in position by small clips lying under the wire bands, the projecting ends of which are bent over the upper surface of the bands before soldering. The main object of these bands is to ensure absolute rigidity of the armature winding when under the action of centrifugal and temperature stresses. The final process comprises the pouring over of the armature with insulating varnish and then thoroughly baking it until a hard non-hygroscopic surface is obtained.

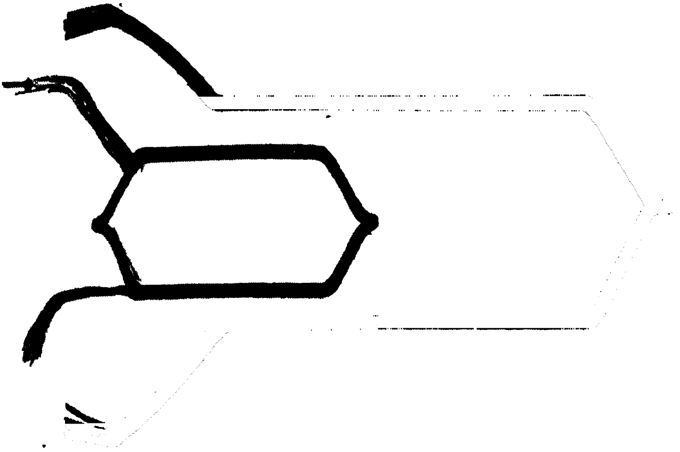


FIG. 26.—FORMED ARMATURE COILS (*Metro-Vickers*)

The projecting lugs at the back end of the commutator bars are known as the "riser" lugs, these being cut out to form a narrow slot into which the ends of the coil conductors are carefully fitted and flood-soldered to ensure full surface contact. Fig. 27 shows armatures partly and completely wound.

FIELD POLES

Main-poles and interpoles are built up of laminated steel sheets, riveted together between steel endplates, and secured by bolts to the machined seatings on the frame. Fig. 28 shows a dismantled field pole with coil and washers, etc.

FIELD COILS

Main series field and interpole coils are made of strip copper conductor, machine wound on formers and insulated between turns with mica. Terminals may be riveted or brazed to the ends of the strip. The coils are then bakelised and pressed to size, after which they are wrapped with mica tape and given a final covering of webbing or glass fabric for mechanical protection. To produce a coil free from any possibility of shrinkage and at the same time render it moisture proof, the practice is to dip the whole into insulating varnish after which it is baked at 120 degrees centigrade.

In the case of compound field coils, the shunt coil is first wound using insulated copper wire and completed in itself with suitable

FIG 27a.—PARTLY WOUND ARMATURE

(*Metro-Vickers*)

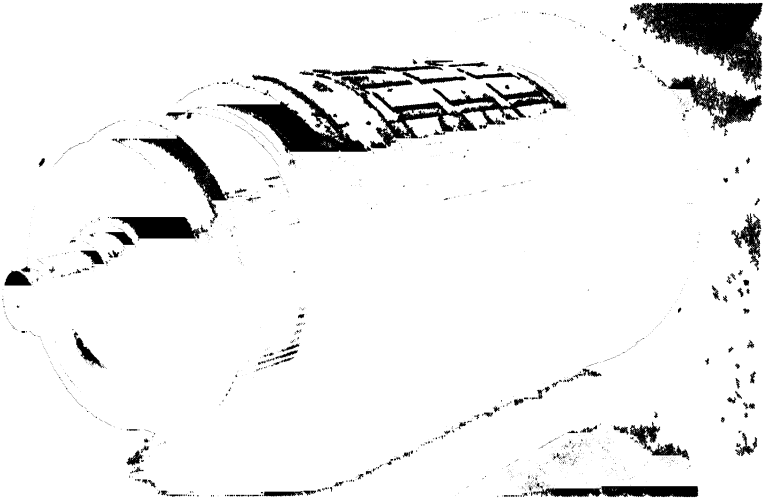


FIG. 27b.—ARMATURE WITH WINDING COMPLETED

(*Metro-Vickers*)

FIG. 28.— FIELD COIL AND POLE DISMANTLED

(Metro-Vickers

outer insulation. After this the series turns are formed radially over the shunt section and the composite coil finally wrapped, varnished and baked.

Tapped series field coils are usually built up in sections but with the layers arranged side by side instead of concentric as is the case with compound coils. This is done owing to the difficulty of bringing out the tapping connections when built up by the concentric method. Fig. 29 shows sections through various field coils.

ARMATURE BEARINGS

The armature bearings may be either of the sleeve or roller types.

Bearings of the former type consist of brass or bronze bushes lined with white metal, in which are machined grooves to distribute the oil over the journal surface, the bushes being fitted and located in the motor end-housings.

Roller bearings are fitted and located in the end-housings and hold several advantages over the older sleeve types, as follows:

(*a*) Considerably higher load capacities are possible with a certain size of journal.

(*b*) A considerable reduction in friction losses is obtained over that of the sleeve type. This is of the order of 5 to 10 per cent.

(*c*) Grease lubrication can be employed with seals to retain the grease, enabling the bearings to be run over long periods of three to six months without attention under normal conditions.

(*d*) Radial wear is reduced to very minute proportions, resulting in much less relative movement between armature and poles. This enables smaller air gaps to be used, a fact which reduces magnetic leakage, reduces the number of coil turns for a certain flux density and also assists in maintaining a more uniform flux distribution. In addition the effects of such relative movement on commutation are eliminated.

Axle bearings necessarily consist of the sleeve type with split bushes located in machined surfaces on the frame by means of steel axle-caps.

LUBRICATION

Sleeve armature and axle bearings are lubricated with oil contained in a substantial reservoir which forms part of the motor end-housings or axle-caps respectively. Oil is syphoned by means of wool or cotton waste to rectangular windows cut in the bearing bush.

Fig. 30 illustrates this type of lubrication. The oil capacity of the reservoirs is sufficient for two to three weeks running.

VENTILATION OF TRACTION MOTORS

In electrical machinery all efficiency losses, i.e. eddy current, resistance drop and bearing and brush friction, etc., are converted into heat. These losses absorb some ten to fifteen per cent of the total power input, depending on the working efficiency of the particular machine. For this reason, all rotating machines must have some form of ventilation to ensure that the ultimate rate of heat dissipation is equal to the heat produced, otherwise damage will be caused by excess temperature. There are three main methods of motor ventilation, viz. totally enclosed, self ventilated and forced ventilated.

In the first case, as the name suggests, the motor is completely sealed off internally from the outside air. This method would appear to be ideal, since no dirt or moisture is admitted into the machine, but such a machine must be relatively large to allow free internal circulation of air, and have a large external surface area to assist heat radiation. The armature is fitted with a fan, usually at the back-end, to ensure that an even temperature of the various parts is maintained. Quite a large number of totally enclosed motors are in operation on railways in this country. Cooling on bogie mounted motors is assisted by the stream of air over the motor frame surfaces, caused by motion of the train. Fig. 31 shows a totally enclosed motor as used on a main line express passenger service, which has its frame cast with ribs in order to increase the surface area. The motor in Fig. 32 is employed on a suburban service.

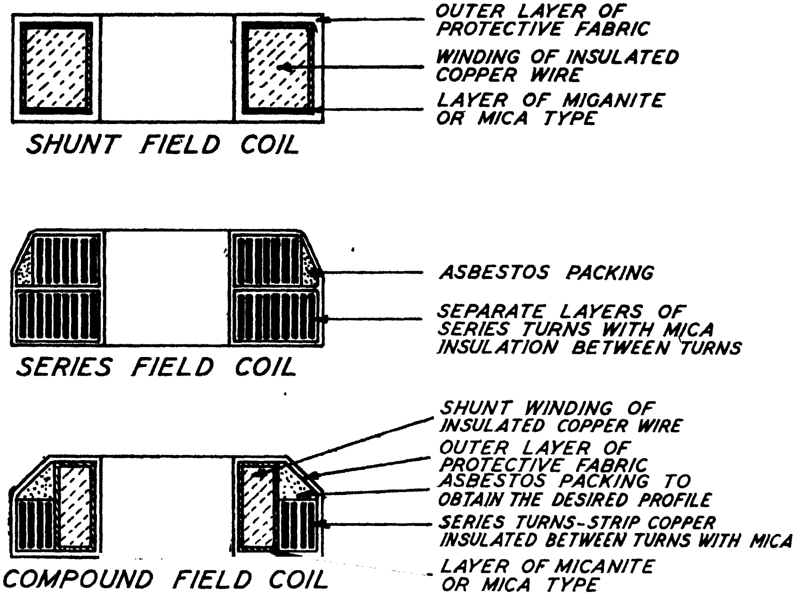
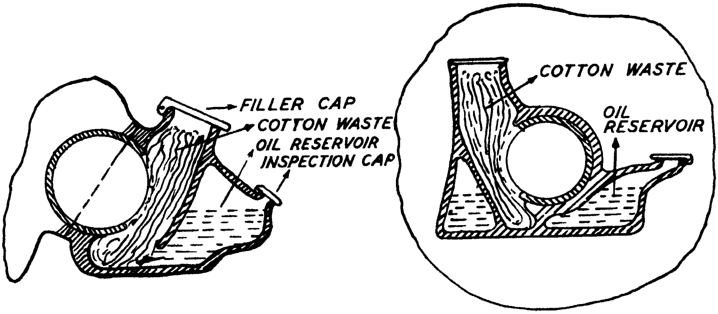


FIG. 29.—DIAGRAMMATIC SECTIONS THROUGH TYPICAL FIELD COILS

Self-ventilated motors are those in which cooling is effected by a flow of free air, entering at one end and being exhausted at the other by a fan mounted on the armature shaft. It is usual to admit cool air through ducts at the commutator end, and exhaust hot air at the fan end through openings which are protected by expanded metal guards against damage to the fan by the entry of foreign bodies. Standard practice is to draw air in through louvres in the coach sides, and after cleaning by passing through a filter or some form of dust trap, it is conveyed by ducts to the motors. Fig. 33 shows a typical self ventilated motor with a single inlet duct at the commutator end, suitable for connecting up to coach air ducts. An illustration of the armature and fan of a similar machine is shown in Fig. 34.

Forced ventilation of traction motors is used essentially in applications where the motor must be capable of high overloads for periods, without any appreciable amount of coasting or light load running, in which case little effective cooling would take place with self ventilation, e.g. as in shunting work. It is also employed where a specified output is required from a motor whose size limitations make self ventilation insufficient for adequate cooling. The cooling air is obtained from a separate blower unit, generally driven by a separate motor, and conveyed to the main traction motors by means of ducts. The armature shaft may or may not be fitted with a fan, which, if fitted, only produces a small proportion of the total air volume involved.



ROAD AXLE BEARING

ARMATURE BEARING (IN ENDPLATE)

FIG. 30.—METHOD OF SLEEVE BEARING LUBRICATION

METHODS OF MECHANICAL TRANSMISSION

The type of transmission used for traction purposes is governed to a large extent by the application.

Tramcars are driven almost universally by single reduction gearing, with single or double bogie driving units, the motors being axle mounted and bolted rigidly to a spring-supported beam. The pinion is carried on the motor armature shaft, and the gear wheel on the main axle, both being enclosed in a steel gear case for lubrication purposes.

Trolley-bus. A chassis mounted motor is used with a univ[illegible]

FIG. 31.—TOTALLY ENCLOSED RAILWAY MOTOR WITH RIBBED FRAME TO ASSIST COOLING

(*Metro-Vickers*)

FIG. 32.—TOTALLY ENCLOSED RAILWAY MOTOR

(*English Electric*)

FIG. 33.—SELF-VENTILATED MOTOR

(*English Electric*

jointed direct drive through a torque shaft to a differential gear unit on the back-axle, both four- and six-wheeled chassis being employed.

Railway Motors. With motor-coach stock the axle-mounted and nose-suspended motor is employed almost without exception. Single reduction gearing is used, generally of the spur type to avoid end thrust, the gears being enclosed in a steel gear-case as for tramway motors.

With locomotives a similar type of motor and suspension has been used on most four or six axle double bogie types, a combination which is still very popular. As the size of such a locomotive is limited by the permissible axle load, larger locomotives are usually fitted with frame mounted motors, employing either a combined drive of the side-rod type, or an individual axle drive, modern design tending to use the latter. The reason for using these latter types is to reduce the dead weight on the driving axles by the maximum possible amount.

SIDE-ROD DRIVES

The types of side-rod drive in common use are:

(*a*) The "*Jackshaft*" drive in which one or more motors drive a common frame mounted shaft, on the ends of which are two balanced cranks. The driving wheels are coupled together in the same way as for normal steam locomotive practice, and a connecting rod is employed to transmit the torque from the jackshaft cranks to the coupled wheels. A drive of this type is shown fitted to the locomotives in Figs. 128 and 155.

(*b*) The "*Scotch Yoke*" is a variation of the jackshaft method, in which the coupled wheels are driven through a triangular framework, with its apex on the crank-pin of the centre coupled axle, and the other two extremities driven by cranks fastened either directly on the two motor shafts or gear-driven from them.

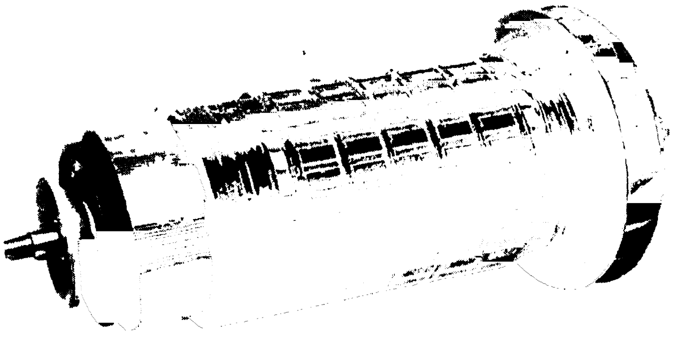


FIG. 34.—ARMATURE AND FAN OF SELF-VENTILATED MOTOR (*B T.H.*)

AXLE DRIVES

Among individual axle drives the following are the more popular in locomotive designs:

(*a*) The "*Buchli Link*" drive (Fig. 36) in which the motor is mounted above and parallel to the axle, the drive being taken by means of a spring pinion and a gearwheel to a link system on the outside of the driving wheels.

(*b*) The "*Quill and Cup*" *drive,* illustrated in Fig. 37, in which the motor drives a hollow quill shaft through reduction gearing, the torque being then transmitted by means of spring cups to the spokes of the driving wheels.

(*c*) The "*Winterthur Universal*" *drive,* utilising two motors per driving axle, mounted in line, parallel to and vertically above it. The drive is taken through an intermediate shaft to a gear wheel on a short sleeve running on the driving axle and flexibly coupled to it by a loose member attached to sliding blocks on the sleeve and the axle. A drive of this type is illustrated in Fig. 38.

TRACTIVE EFFORT AND SPEED-TIME CONSIDERATIONS

Tractive power is considered in terms of power output at the wheel tread, whether on railway or road transport equipment, and consists of two components, namely, the "tractive effort" in pounds and the speed in miles-per-hour. These in turn determine the capacity and characteristic of the motor required.

TRACTIVE EFFORT

In train or vehicle motion the tractive effort must be sufficient to provide for:

(*a*) The required acceleration to meet schedule demands.

(*b*) Overcoming the normal train resistance, this comprising air pressure and friction, axle bearing and rolling friction of the wheels on the track or road.

(*c*) Negotiation of the steepest gradients and curves on the route.

SPEED AND TRAIN MOTION

Speed is considered from two points of view, that of *schedule speed*, which is distance between stops considered with respect to the total time taken including stopping time. Secondly *average speed*, which is the distance between stops considered with respect to the running time only.

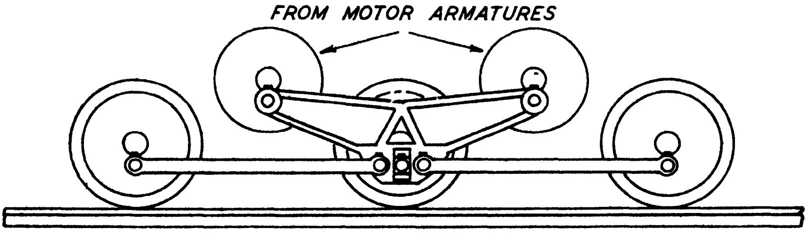


FIG. 35.—THE "SCOTCH YOKE" DRIVE

SPEED-TIME CURVES

The schedule time between any two stops, may be split up into five intervals of time.

FIG. 36a.—BUCHLI LINK DRIVE, GENERAL VIEW SHOWING WHEELS AND AXLE
(*Institution of Electrical Engineers*)

(*a*) The initial accelerating time, from rest up to a point where all the motor starting resistance steps have been cut out, the tractive effort during this period being approximately constant.

(*b*) The speed curve accelerating time, during which normal voltage is applied to the motors, the tractive effort and rate of acceleration steadily decreasing with increasing speed. This period may also include an amount of running at constant speed and tractive effort when the distance between stops is considerable.

(*c*) The coasting period, which takes place after the maximum desired speed has been attained and the power cut off.

(*d*) The braking period, being the time during which any form of braking is being used and continuing until the vehicle is at a standstill.

(*e*) The stationary period.

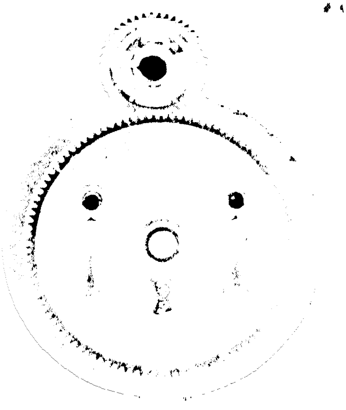


FIG. 36b.—BUCHLI LINK DRIVE, CLOSE UP OF DRIVING GEAR, WHEEL AND LINKS
(*Institution of Electrical Engineers*)

For any service, information regarding the proposed speed-time curves, together with the type of rolling stock, loading and route contours, supplies the traction engineer with sufficient data to enable him to work out the capacity, rating, and characteristics of a motor suitable for that service.

The physical size of a traction motor determines the maximum torque obtainable, in that the torque is proportional to the diameter and length of the armature. The size of motor which can be accommodated in the case of axle mounted machines, is limited by the track gauge and ground clearance, the latter limitation being illustrated in Fig. 40.

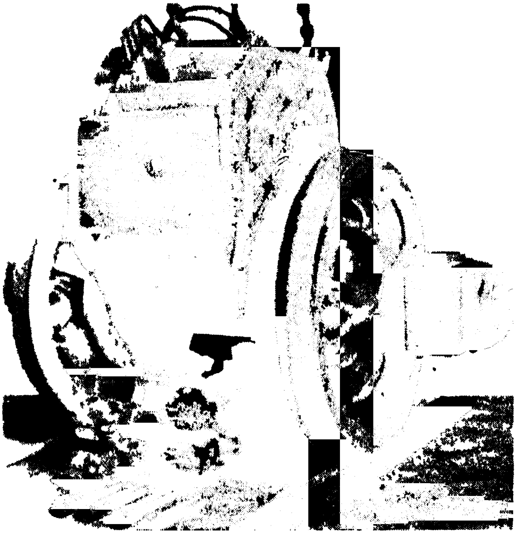


FIG. 37.—QUILL AND CUP DRIVE

(*English Electric*)

On all types of equipment however, the maximum tractive effort is definitely limited by the axle loading and the wheel adhesion factor.

RATING OF TRACTION MOTORS

Having studied the various factors limiting traction motor outline, coupled with the required output, the question of rating arises, rating being defined as power output with respect to time.

As seen from the speed-time curves in Fig. 39, the "power on" period is only part of the total running time, heavy load occurring mostly during initial acceleration, so that the motors are able to cool during light load running and coasting with "power off".

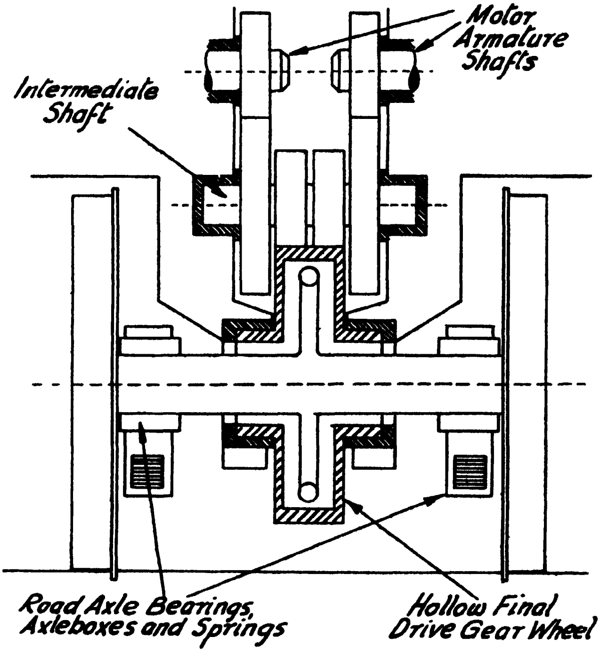


FIG. 38a.—CROSS-SECTION THROUGH WINTERTHUR UNIVERSAL DRIVE, SHOWING DETAILS OF DRIVE AND SPIDER ON MAIN AXLE. FOR ASSEMBLY OF FLEXIBLE DRIVE, SEE FIG. 38b BELOW

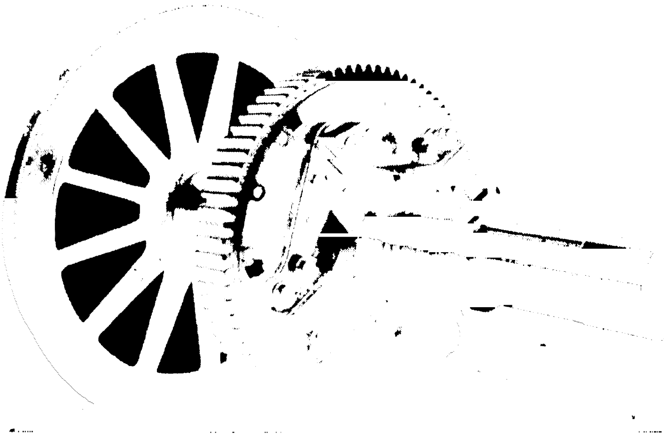
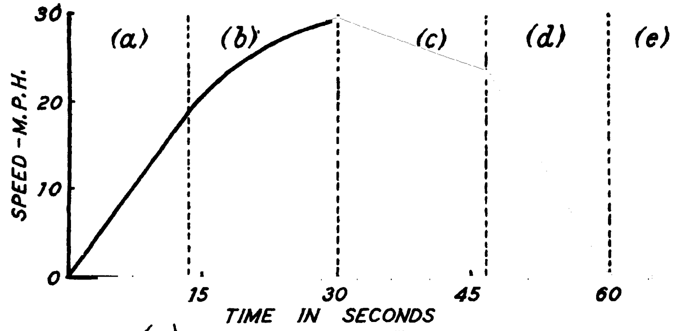
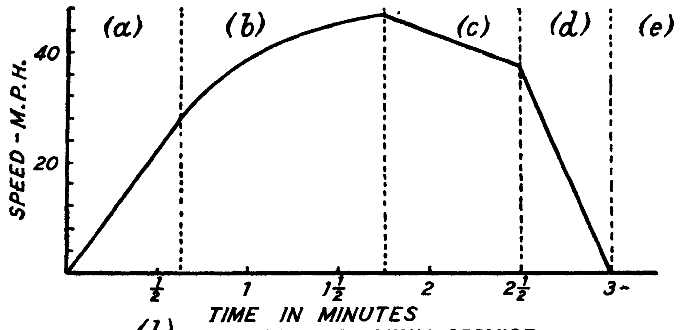


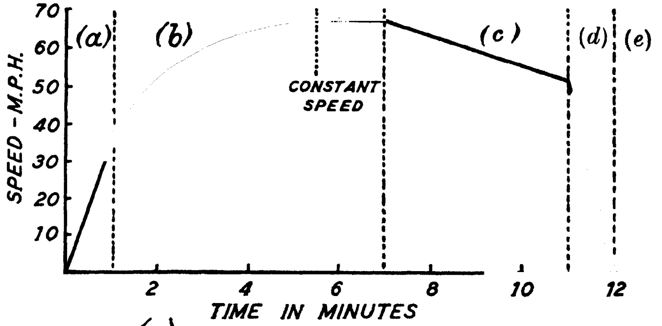
FIG. 38b.—FLEXIBLE DRIVE ASSEMBLY WITH ONE HALF OF GEAR WHEEL AND ENCLOSING COVER REMOVED (*Swiss Locomotive and Machine Works, Winterthur, Switzerland*)



(a) TROLLEY BUS QR TRAMWAY SERVICE



(b) SURBURBAN RAILWAY SERVICE



(c) EXPRESS RAILWAY SERVICE

FIG. 39.—TYPICAL SPEED-TIME CURVES

(*a*) Initial Accelerating Period; (*b*) Speed-Curve Accelerating Period; (*c*) Coasting Period; (*d*) Braking Period; (*e*) Standing Period

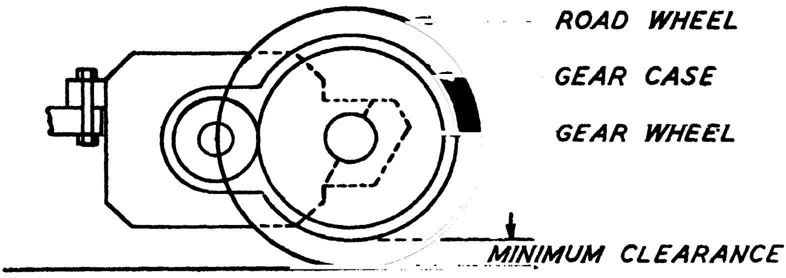


FIG. 40.—MINIMUM GROUND CLEARANCL

For this reason it is usual to rate traction machines on the short time basis of one hour, the actual continuous rating being in the order of 60 to 80 per cent of the one hour rating for ventilated, and up to 45 per cent for totally enclosed machines. The definition of the one hour rating is, "the load at which the motor can operate continuously for one hour, under test stand conditions, at full nominal line voltage without exceeding the maximum temperature rise in any part of the machine". The B.E.S.A. temperature specification for traction equipment is given in chapter nine.

Fig. 41 shows a speed-time curve for a suburban type service, with the corresponding current curve. The traction motor continuous rating should not be less than the "root mean square" current value for the service.

Fig. 42 shows the characteristic curves of a 235 horse-power tapped field traction motor, rated for one hour at 580 volts, 340 amperes, and with a continuous rating of 184 horse-power at 580 volts, 235 amperes. It is used on motor-coach stock and is

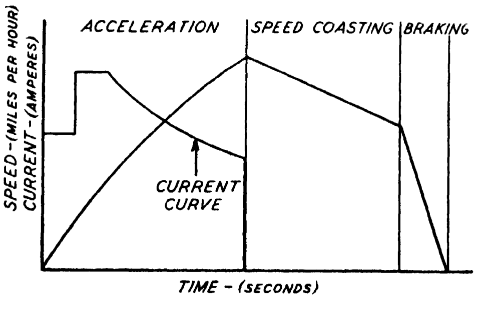


FIG. 41.—CORRESPONDING SPEED-TIME AND CURRENT-TIME CURVES

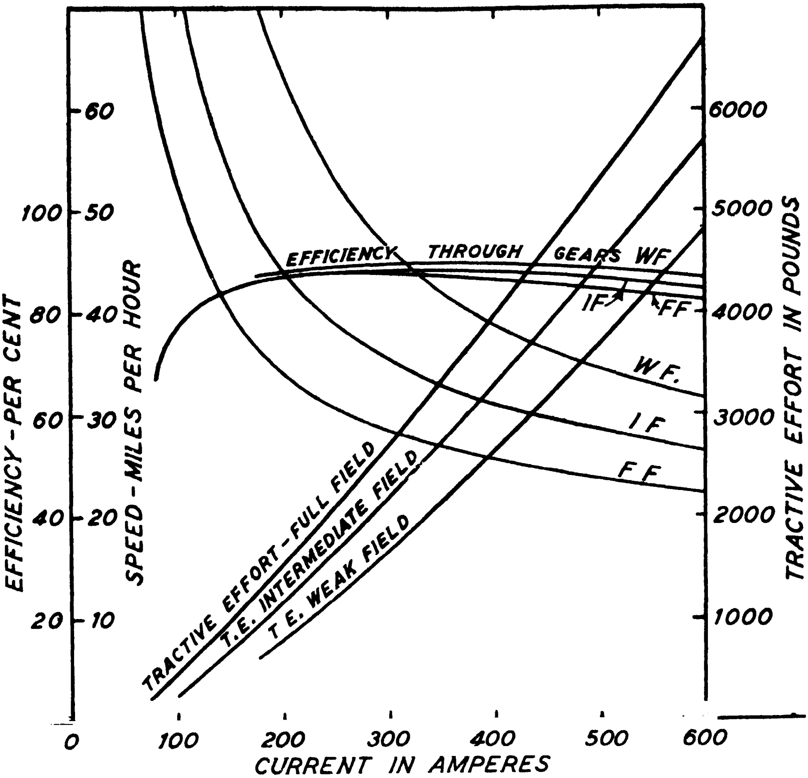


FIG 42 —CHARACTERISTICS OF TAPPED FIELD RAILWAY MOTOR

of the self-ventilated type, the series field coils being arranged for tappings giving full and weak field strengths. The normal accelerating tractive effort is 4,000 to 5,000 pounds at the wheel tread. This machine is of the four-pole type with a lap wound armature and four-arm brush gear.

FEATURES OF THE MODERN TROLLEY-BUS MOTOR

In recent years the modern trolley-bus has come more into the foreground as a successful means of street electric traction, mostly due to the development of the compound motor so as to have a wide speed range, coupled with high accelerating and limited braking torques. Previously it had been the practice to use a system very similar to that for tramways, employing series-parallel control of a motor unit with two armatures on the same

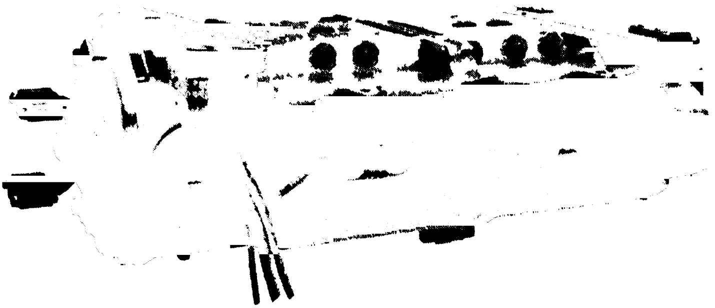


FIG. 43.—TWIN ARMATURE TROLLEY-BUS MOTOR

(*English Electric*)

shaft (Fig. 43). The motor was of the plain series type and consequently only rheostatic braking could be incorporated in the electrical equipment.

The modern tendency is to use single motor equipments with field regulation so used as to give a minimum speed of 10 to 12 miles-per-hour with full line voltage applied to the motor, and a maximum speed of 35 miles-per-hour on weak field. Such performance is most satisfactorily obtained by using shunt field variation and diverting or tapping the series field. The motor is run as a series machine for maximum speeds, and as a compound motor for starting and low speed running. The practice of utilising the reverse torque as a generator for retarding the vehicle has been developed, and is used on all types of trolley-buses. Regeneration to the supply is obtained at the higher speeds, and rheostatic braking on the starting resistances down to four miles-per-hour. Purely regenerative braking has limited advantages, owing to the incapability of many power supply stations to absorb the regenerated energy in the event of no other load being in a receptive condition. This results in voltage surges damaging to the equipment. For this reason circumstances have forced the development of rheostatic braking systems. Fig. 44 shows typical characteristic curves of a 80 horse-power trolley-bus motor designed for full regenerative braking. Fig. 45 shows those of a similar motor arranged for rheostatic brake with

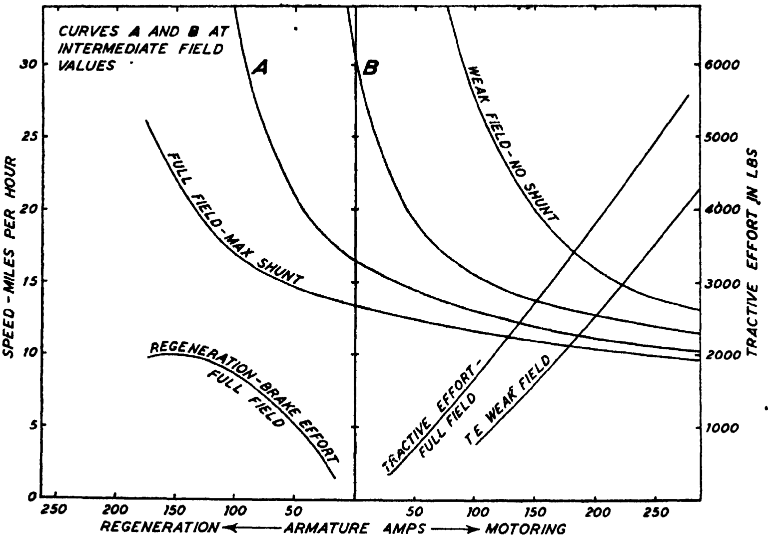


FIG. 44.—CHARACTERISTICS OF 80 H.P. TROLLEY-BUS MOTOR DESIGNED FOR REGENERATIVE BRAKING

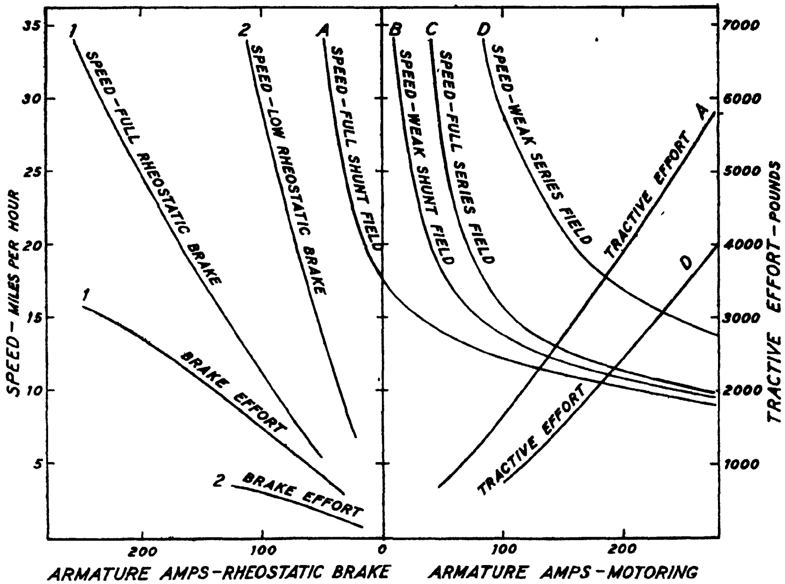
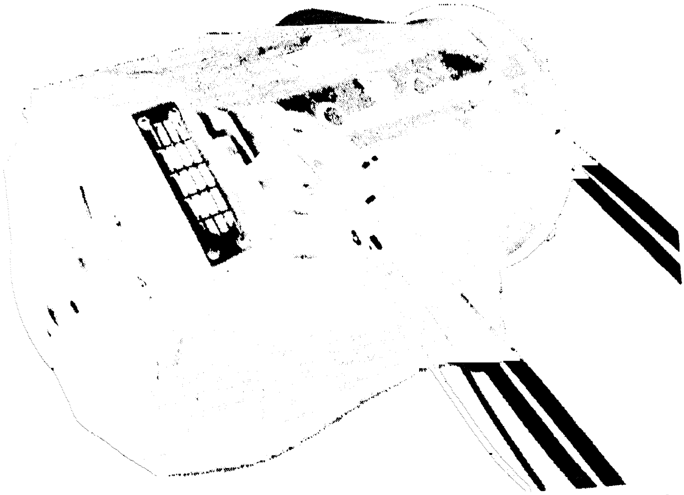


FIG. 45.—CHARACTERISTICS OF TROLLEY-BUS MOTOR FOR RHEOSTATIC BRAKING (Limited Regeneration down to 20 m.p.h. only is possible—see portion of curve *A* to left of centre line)



(Metro Vickers)

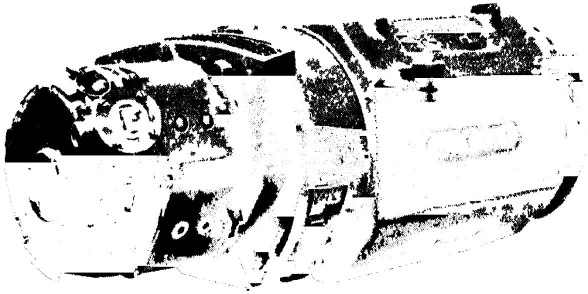


FIG 46—TYPICAL TROLLEY-BUS MOTORS (English Electric)

regeneration down to 20 miles-per-hour. Fig. 46 shows typical trolley-bus motors.

Chapter 3

THE CONTROL OF TRAMWAY AND TROLLEY-BUS MOTORS

IN order to control the starting and stopping of the motors on a tramcar or trolley vehicle, it is necessary to have some form of control over the application of the voltage from the trolley-collector to the traction motors. In its simplest form this would consist of a switch of some kind which when closed would apply full line voltage to the motors. This, however, is not practicable, as the maximum current which can be handled by any traction motor is limited by its commutating capacity and by mechanical considerations. With a normal speed-torque characteristic, the initial starting current of the motor if switched direct on to the line would be sufficient to cause severe damage to the brushgear, commutator and windings. Also, the torque exerted would be so high and of such violence as to damage the drive to the road axle by breaking gear teeth, etc.

Even if a motor could be so designed that mechanically it could withstand all these stresses, another limiting factor comes into play. The maximum torque which can be exerted without wheel-slip is limited by the weight on the road axle and the friction between the driving wheels and the road. For a given weight on the axle, it is possible to exert a considerably larger tractive effort on a trolley-bus with rubber-tyred wheels, than on a tramcar with steel wheels and track, hence it is possible to use a higher rate of acceleration with a trolley-bus than with a tramcar.

The ideal starting arrangement is thus to keep the torque during the accelerating period below that corresponding to the maximum tractive effort, but reasonably near to it. This can be done by having several starting positions in sequence operated by a controller handle. Torque being proportional to current, the obvious way of obtaining this control is to insert a resistance of several steps in series with the motor, these steps being cut out in a predetermined order, pausing on each step to allow the motor to accelerate. Rapid acceleration is thus obtained to a point corresponding to full line voltage on the motor without exceeding the current value corresponding to maximum tractive effort.

DUTY-CYCLE

On a tramway system the distance between stopping places is relatively short, and it is necessary to accelerate from rest at very frequent intervals. Obviously, under such conditions, the starting resistance is in circuit for a considerable part of the time during which power is applied to the motors. As two motors are always employed, it is possible by using "series-parallel control" to effect a considerable saving in the power which would otherwise be wasted in the starting resistance, and in addition, to obtain widely differing continuous running speeds, a condition very desirable for traffic negotiation.

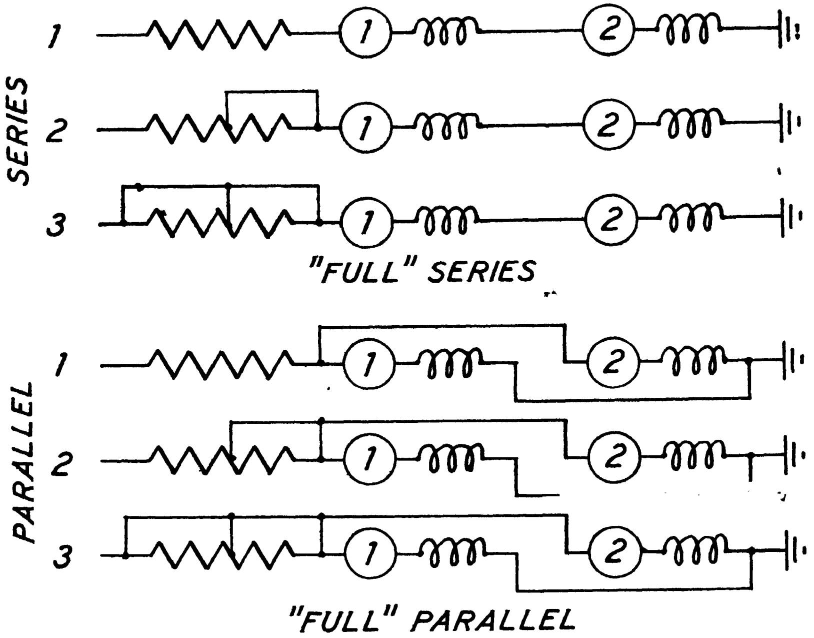


FIG. 47.—SERIES-PARALLEL CONTROL FOR TWO MOTORS

SERIES-PARALLEL CONTROL

This control is applied to a tramcar by connecting both motors in series for the first portion of the starting cycle. On moving the controller handle to notch 1, the starting resistance is connected in series with the two motors and line volts applied to the combined circuit. This resistance is then cut out step by step until the motors are connected direct to the line, a position known as "full series", at which each motor will have one half of the line voltage applied to it. Continuing, passing through the stage known as "transition", the two motors are now connected in parallel and the starting resistance reinserted in series with them, a position known as "first parallel". To accelerate further, the resistance is again cut out step by step until finally each motor is connected directly to the line, the "full parallel" notch. Fig. 47 shows a diagrammatic representation of the circuits on certain of these accelerating positions.

The two running speeds are obtained in the "full series" and "full parallel" positions where none of the starting-resistance is in circuit.

Saving in energy consumption is obtained in the series positions where only one resistance is necessary to feed both motors. Consequently it will only be required to absorb a smaller proportion of the line voltage than would be the case if both motors were permanently connected in parallel. This type of control is almost universal where two or more traction motors are used.

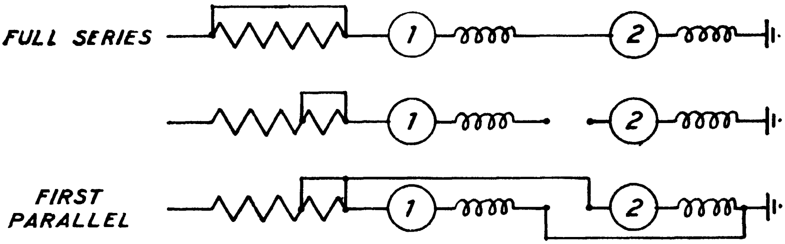
TRANSITION

The change-over from "full series" to "first parallel" notches is known as transition, three different methods being available for carrying out this re-grouping and connecting of the motors.

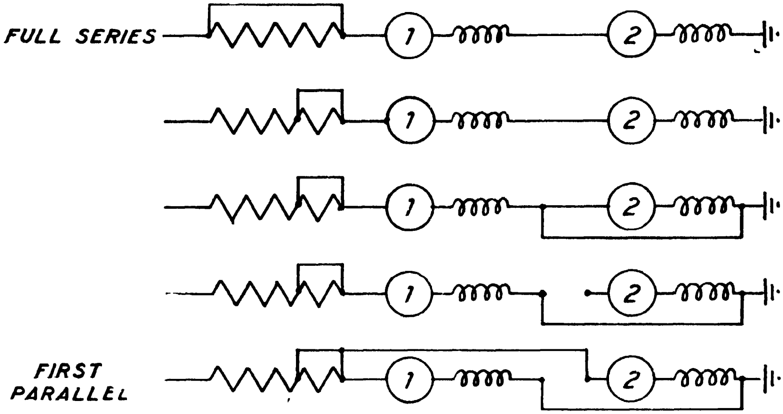
(*a*) "Open-circuit transition" in which the series connection between the two motors is first broken, the starting resistance is then reinserted, and the motors reconnected in parallel. (Fig. 48a.)

(*b*) "Shunt transition". In this method the starting resistance is first reinserted. The interconnecting point between the two motors is then earthed and finally No. 2 motor disconnected from this point and reconnected in parallel with No. 1 motor. (Fig. 48b.)

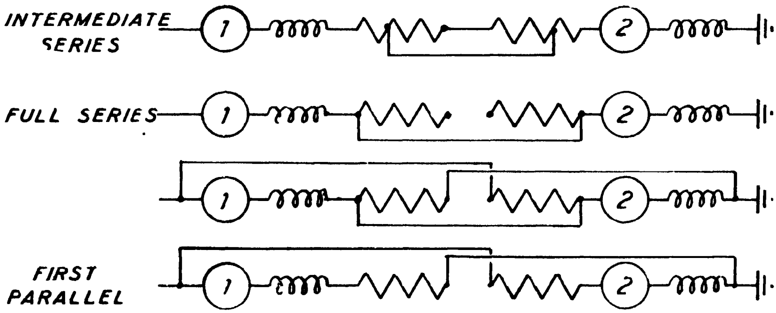
(*c*) "Bridge transition" may only be employed in connection with a starting resistance split up into two equal halves which in the series positions are connected between the motors. On the final series notch the two motors are connected together by a link, while the other ends of the starting resistances are open-circuited. Transition is



(a) OPEN-CIRCUIT TRANSITION



(b) SHUNT TRANSITION



(c) BRIDGE TRANSITION

FIG. 48.—METHODS OF TRANSITION

effected by connecting each starting resistance to the remote line terminal of the opposite motor, and then opening the series link between the motors. (Fig. 48c.)

Open-circuit transition is very rarely used. Shunt transition is used on all tramway work, most industrial locomotives and also on main-line locomotives when the operating voltage is above 600 volts. Its chief disadvantage lies in the fact that the tractive effort of No. 2 motor disappears during the transition period.

Bridge transition is used on suburban motor-coach stock as the tractive effort of both motors is maintained throughout the process, thereby eliminating any possibility of a snatch which may cause breaking of couplings, etc. On voltages above 600, however, heavy arcing results on opening the series link due to the higher inductances of the motors, and two pairs of contacts in series are necessary to reduce the burning.

CONTROLLERS

To obtain the various combinations of motors and resistances in the correct order through series transition and parallel notches, a controller of the drum type is usually employed. The handle of this controller rotates a drum or cylinder which carries a number of copper segments grouped in sections where necessary, these sections being insulated from the drum shaft and from each other. The various segments make contact with fixed contacts or fingers at different angular positions of the controller drum. These fingers are mounted on an insulating bar and to them are connected the supply, the motors, and the starting resistance.

Fig. 49 shows a typical non-reversing controller cylinder layout, the notches being indicated as dotted lines, and the circuits and connections being tabulated separately. Shunt transition is employed. The black dots represent the fingers, and the horizontal blocks the segments linked where shown.

As it is always necessary to be able to reverse a tramcar equipment even though a controller may be provided at each end of the vehicle, arrangements must be made so that the motors may be run in either direction from either end of the car. Standard practice is to incorporate the necessary reversers in the way of an additional cylinder in the controller frame, this cylinder being smaller than the main speed regulating one, and making contact with a separate set of fingers. From the "off" position, rotation

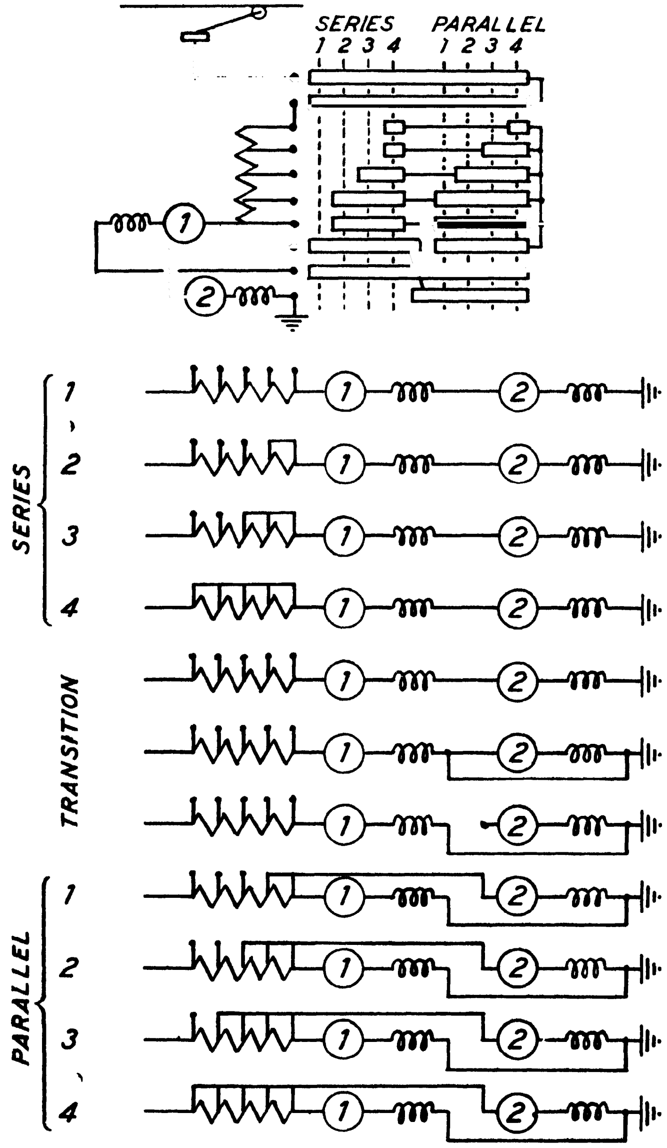


FIG. 49.—CIRCUIT DIAGRAM AND STEP BY STEP CIRCUITS, SIMPLE SERIES-PARALLEL CONTROLLER

of the reverse cylinder through an angle of about 60 degrees in one direction brings the segments and fingers into the "forward" or "ahead" connection, and rotation in the opposite direction a similar amount gives "reverse" connections. Reversal is actually obtained by changing over the armature connections without disturbing those of the field. Fig. 50 shows the controller circuit dealt with earlier modified to include a reversing cylinder.

Mechanical interlocking is always provided so that the main controller handle can only be moved when the reversing cylinder is in the forward or reverse position. Also, once the main control cylinder has been moved from the "off" position, the reversing cylinder is locked. This latter is operated by a key which is detachable in the "off" position, so that by allocating only one such reverser key to each car, only one controller can be made operative at a time, so avoiding circumstances which might have disastrous results on the equipment.

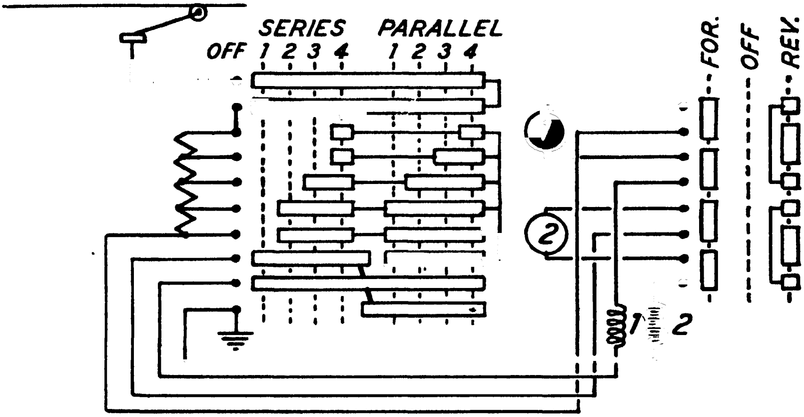


FIG. 50.—SERIES-PARALLEL CONTROLLER WITH REVERSE CYLINDER

TAPPED FIELD CONTROL

Tapped field control is employed where it is desirable to have more than the two running notches provided by ordinary series parallel control. If one tapping is provided on each motor field, then two speeds are obtainable in series and two in parallel, giving four in all. Similarly six speeds may be obtained by using two tappings on each field. An alternative method giving the same result as the single tapping system, is obtained by shunting

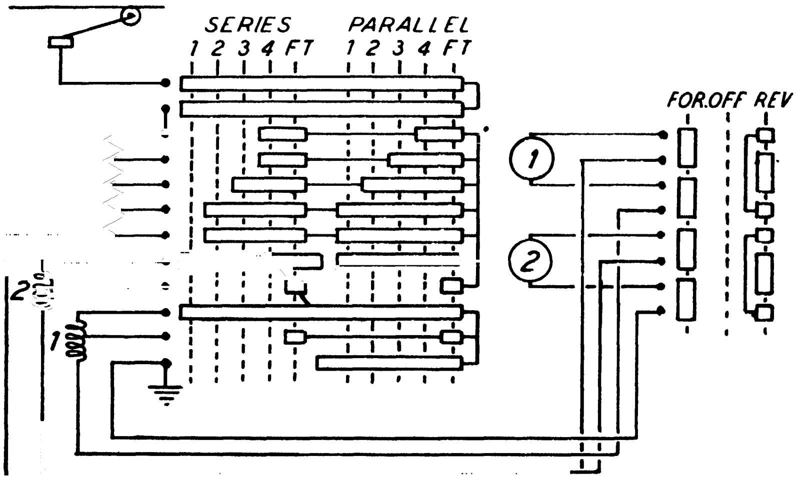


FIG. 51.—SERIES-PARALLEL CONTROLLER LAYOUT WITH REVERSER AND FIELD-TAP CONNECTIONS

each field with a resistance so as to divert some of the current away from the field coil. In actual practice the most popular system employed when more than two running notches are required is that of having a tapped field motor, but only using the tappings in the parallel running position, this giving one speed at "full series" and two or more at "full parallel". Fig. 51 shows the controller circuits now including field tapping on this principle.

MAGNETIC BLOWOUT

In order to avoid excessive burning of the fingers and contacts when the circuits are interrupted, provision must be made to extinguish the arc which forms as the contacts open. This is accomplished by fitting a magnetic blowout. To understand this a return is made to the fundamental principle that a wire carrying a current in a magnetic field is acted on by a force tending to move it at right angles to the field and to its own axis. Now, if the wire be replaced by an arc between two contacts, the arc may be regarded as the wire carrying the current and will be acted on by a force tending to move it away from the contacts, the direction being according to the polarity of the imposed magnetic field.

By using a coil which carries the contact current to form an electro-magnet, and transferring the flux from the latter to the contact area by means of pole pieces, correct polarity of the magnetic field for ejection of the arc is ensured. Fig. 52 represents this diagrammatically, and it will be seen that following the fundamental principle with the coil wound as shown and current passing in the direction indicated, the arc will be ejected as shown by the arrow and rapidly extinguished. The pole pieces are protected from the arc by the use of an "arc chute", a box made of arc-resisting material which encloses the arc in the contact area. The blowout coils are usually placed in the leads to the fixed contacts and often form part of the fixed contact unit itself.

Another type of blowout unit is obtained by passing the current from the line round several coils, each coil being opposite a finger. The former on which these coils are wound has pole pieces between each coil and these form the magnetic fields required, correct polarities being provided by winding the coils on the former in the requisite direction The whole assembly is placed in an insulating tube and fitted in an arc chute assembly which contains all the arc chutes necessary. This type of unit is very convenient for use in controllers, as the whole blowout unit is removable in one piece, and when removed interrupts the controller feed so preventing operation when the unit is not in its place. The controller illustrated in Fig. 55a has a blowout of this

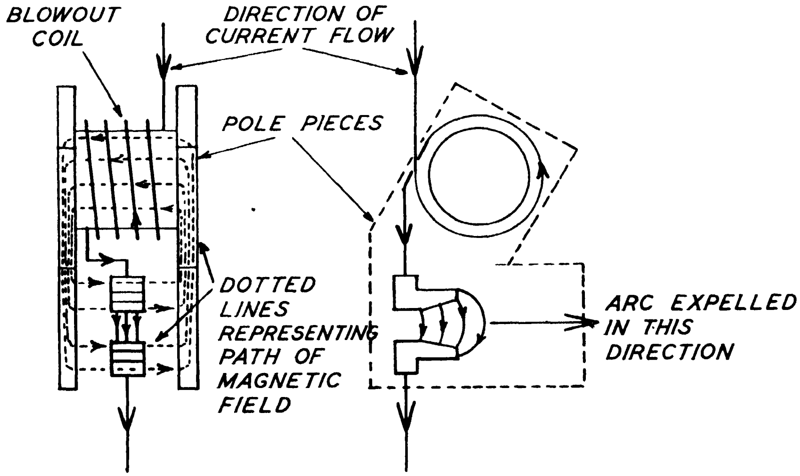


FIG. 52.—DIAGRAMMATIC ARRANGEMENT OF MAGNETIC BLOWOUT FOR ARC RUPTURING

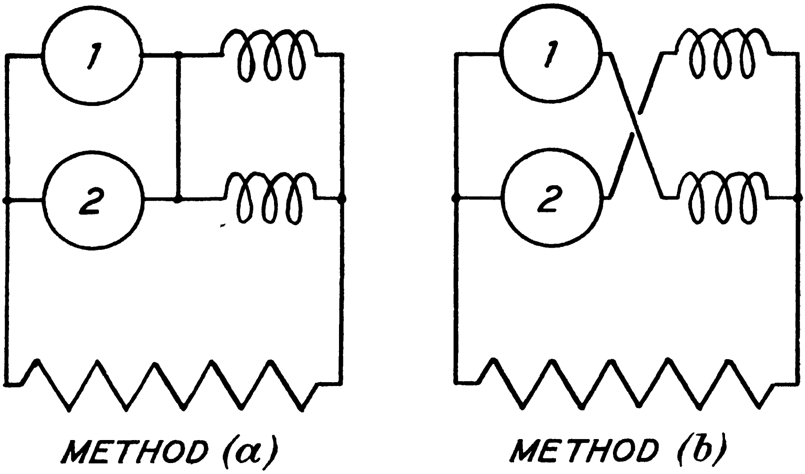


FIG. 53.—BRAKING CONNECTIONS

type fitted, its position in the circuit being in the lead from the second finger on the power terminal bar to the starting resistance.

TRAMWAY CONTROLLERS

Tramway regulations require the provision of an electric brake to assist in bringing the car to rest rapidly if necessary. Certain controllers for use in hilly districts also have a run-back preventer, which brakes the car automatically if it tends to move in the opposite direction to that to which the reverse cylinder is set. The methods adopted to obtain these special functions are outlined in the following paragraphs.

ELECTRIC BRAKES

To obtain a braking effort from a pair of traction motors, it is necessary to re-connect their fields and armatures in such a way that they will function as self-excited series generators. A resistance is then connected across the terminals of these machines and obviously the energy dissipated in this resistance must come from the kinetic energy of the tramcar. Hence a retarding effort will be exerted on the vehicle proportional to the energy dissipated in the resistance so that control of the braking may be effected by variation of this load resistance.

In order to obtain re-generation as series generators from any pair of traction motors, the following conditions must be observed:

(*a*) The armatures and fields must be reversed relative to each other, and it is more usual in practice to reverse the fields.

(*b*) The two motors must be connected in parallel otherwise excessively high voltages may result.

(*c*) The maximum value of the load resistance must be lower than the critical value which will prevent the machines from building up as self-excited generators.

When the machines are operating as generators in parallel, some form of stabilisation between them is necessary in order to equalise the loading and consequently the brake effort on each axle. Two methods of stabilising are used, the connections being shown in Fig. 53. In Fig. 53a a stabilising connection is placed between the two motor circuits to equalise the field currents, while in Fig. 53b stability is obtained by exciting each field from the alternate machine. Each system has its advantages and disadvantages. In the former case braking is only possible when the car is moving in the direction to which the reverse cylinder is set, and in the event of the car moving in the other direction, e.g. running backward, the brake is not operative until the reverse cylinder has been moved to the corresponding position. However, in the event of the failure of one motor, effective braking still continues on the other one. With the latter (cross-connected) system an emergency brake is provided against running backward, as, on a reversal of direction, the motors become a pair of short-circuited series generators with powerful braking results, but in the event of a defective machine, the braking power of this system may be considerably reduced.

The modifications necessary to the main power cylinder to enable braking to be used consist of fitting several extra segments and fingers for reversing the motor fields, together with arrangements for connecting the machines in parallel, stabilising them, and loading them across a variable resistance. The circuit diagram and cylinder development of a complete tramway controller is shown in Fig. 54, the extra segments for obtaining braking being at the lower end of the power cylinder. The fingers which contact these segments are not fitted with arc-suppressing arrangements as the segments are so placed that on no occasion is any current ruptured on them. Braking connections are of the type shown in Fig. 53a, the variation in loading resistance being obtained by means of extra segments on the power cylinder brought into action by moving the controller handle from the "off"

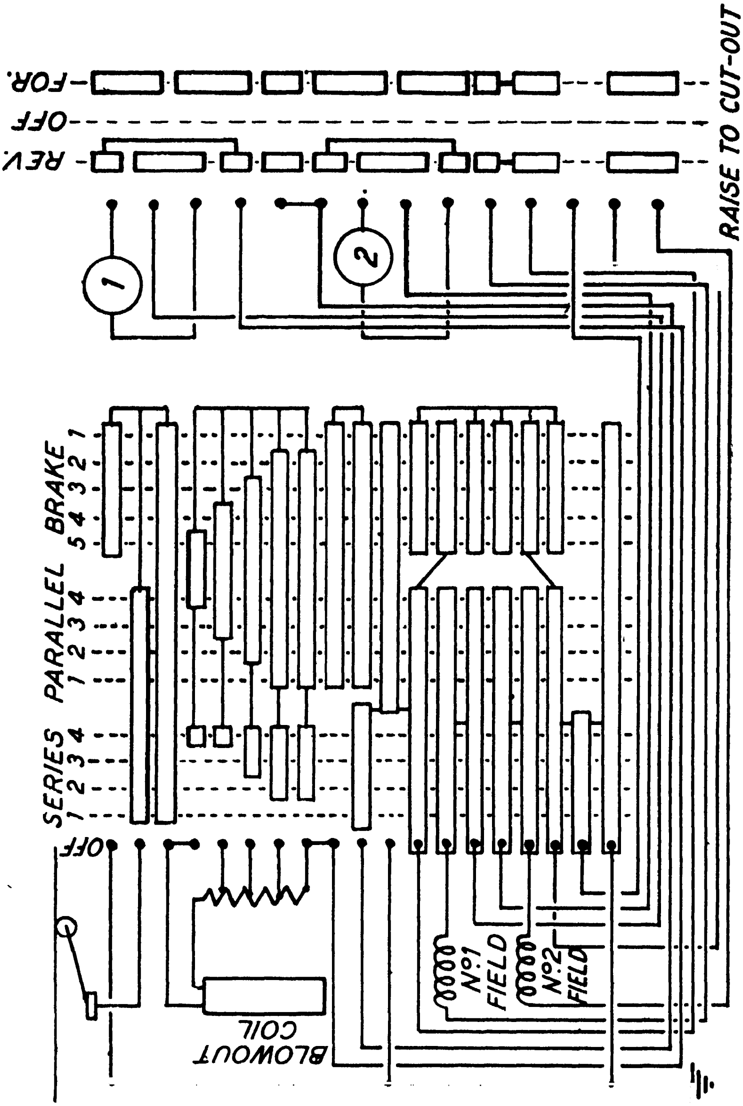


FIG. 54.—COMPLETE CIRCUIT DIAGRAM OF TRAMWAY CONTROLLER

position in the opposite direction to that for "power". The normal starting resistance is, of course, used for braking, and, if the electric brake is to be used for service stops, this resistance must be suitably rated to carry the starting and braking currents.

When it is desired to have an automatic run-back brake with this type of controller, extra segments are fitted which short-circuit one traction motor in the "off" position. Obviously with this connection there will be no effect when the motor is rotating in the normal direction, but should it attempt to move in the reverse direction, it will immediately build up as a short-circuited series generator and so reduce the speed of the car to a crawl.

MOTOR CUT-OUT

Several methods of arranging to disconnect one motor in the event of its failure are in use. In brief they are the following:

(*a*) A reversing drum so designed that it may be raised and lowered relative to the fingers, i.e. along its own axis, in order to disconnect the segments from the fingers corresponding to the appropriate motor. To ensure that this is not done when power is being supplied, it is customary to use the reverser key as a detachable handle for raising and lowering the cylinder.

(*b*) A small motor cut-out drum, in addition to the power and reverse cylinders, operated by the reverse key, and with segments and corresponding fingers to enable one or other of the motors to be disconnected.

(*c*) A reverse cylinder with extra positions and segments.

(*d*) Double throw switches mounted inside the controller.

(*e*) Special fingers fitted with cams or levers to enable them to be raised from contact with the reverse drum, and there locked in position.

With the first four methods it is usual to short-circuit the defective motor and, by means of a mechanical stop, prevent the main power cylinder from going beyond the "full series" position. With the last method, however, power is only obtained in the parallel positions.

It is customary to fit a notched wheel on the power cylinder and a notched quadrant on the reverse cylinder, these engaging with spring catches on the controller frame. The notches are so placed as to give the correct positions to the cylinders at each starting notch, thus enabling the operator to locate each one easily. Certain types of controller also have a "notching regulator", a device which, operating on the ratchet principle, makes it necessary to make a definite pause on each notch. This has the advantage of preventing the driver from cutting out two steps of resistance at the same time with consequent overloading of the motors.

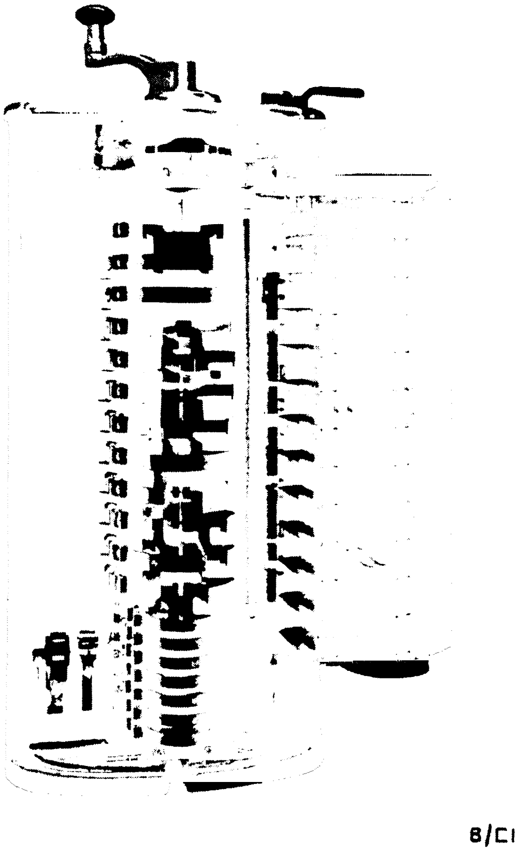


FIG. 55a.—TRAMWAY CONTROLLER
(*English Electric*)

The controller diagrammatically shown in Fig. 54 has most of the features discussed in this chapter including a motor cut-out operated by raising and lowering the reverse cylinder, and many tramcars now operating in this country have these identical circuits for control of their motors.

TYPICAL CONTROLLERS

Fig. 55 shows four modern tramway controllers.

FIG. 55b.—TRAMWAY CONTROLLER

(*English Electric*)

(*a*) This is a two motor controller with removable blowout as described on page 63, and a motor cut-out switch operated by raising and lowering the reverse cylinder.

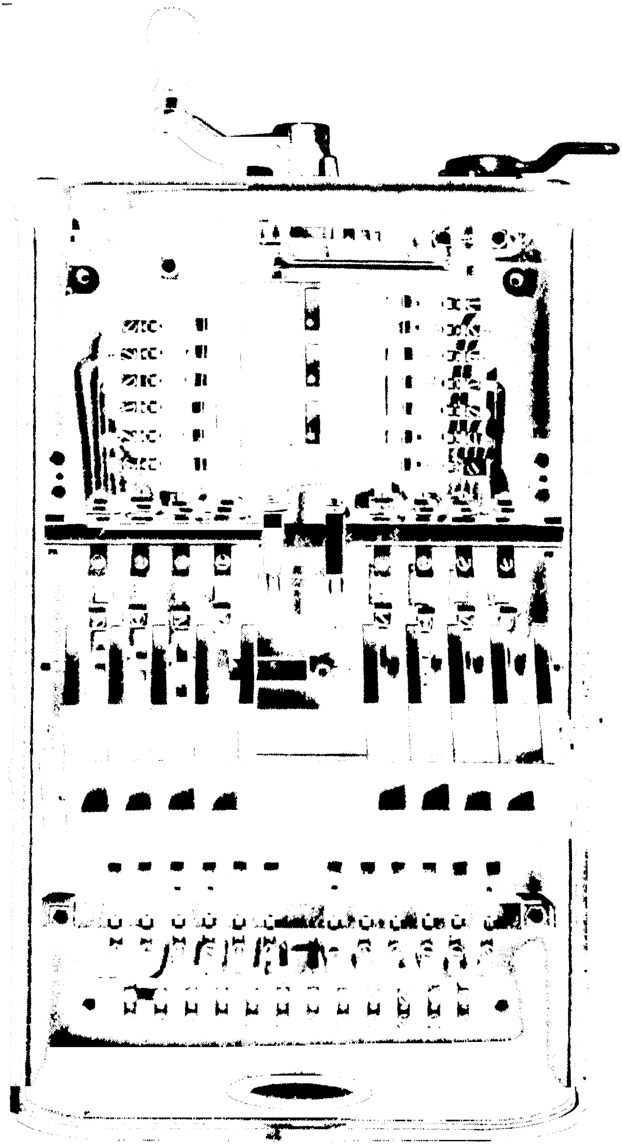


FIG. 55c.—TRAMWAY CONTROLLER

(*Metro-Vickers*)

It has either four or five series, four parallel and seven brake notches, braking connections being obtained on the smaller segments at the lower end of the main controller cylinder. It is capable of series-parallel control on two motors of up to 50 horse-power each, operating on 600 volts.

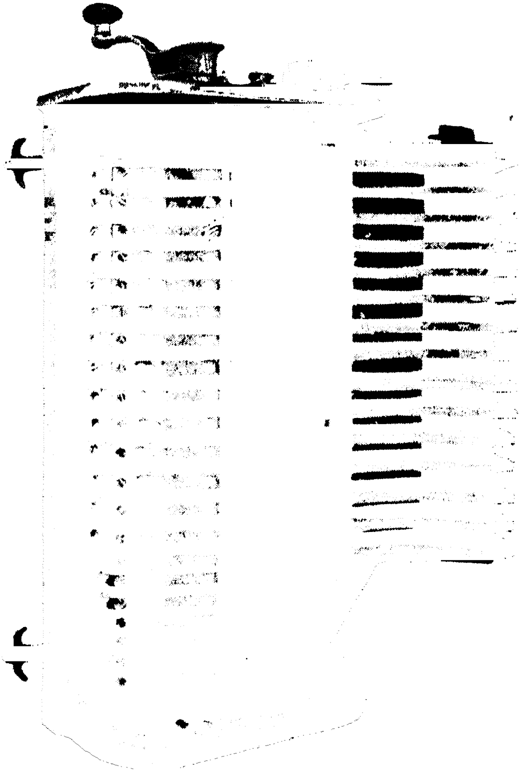


FIG. 55d.—TRAMWAY CONTROLLER

(*B.T.H.*)

(*b*) This is a development from the previous type. The lay-out is similar, but each set of contacts has its own blow-out assembly, all the arc chutes being on a detachable frame. All fingers and drum segments are replaced by fixed and moving contacts respectively, the circuits being operated by closing these contacts by means of cams

FIG. 55e.—CLOSE-UP OF TRAMWAY CONTROLLER CAMSHAFT

(*Metro-Vickers*)

mounted on the main controller shaft. Brake-power changeover and motor cut-out are as for type (*a*) and two motors up to 80 horse-power each can be controlled satisfactorily.

(*c*) This is also a cam-operated controller, but has a horizontal camshaft instead of a vertical one (see Fig. 55e). Motor cut-out is obtained by extra positions on the reverse drum, which consequently is larger in size, is mounted loosely on the main spindle and operated by linkage. Power-brake changeover is carried out by a special drum mounted below the camshaft and automatically set to its correct position.

(*d*) This type is similar to that described first, except that the motor cut-out switch is an entirely separate drum with its own contact fingers. It is operated by means of the reverser key which fits on to a spindle projecting through the top-cap of the controller.

Types (*b*) and (*c*) are sometimes used for the control of tramcars equipped with four traction motors, usually of the 300 volt type. Each two motors are connected permanently in series, their connections to the controller being the same as if each pair were one motor only.

There are many types of tramway controller, but all types will be easily understood by referring their various components to those described earlier in this chapter.

CIRCUIT BREAKERS

In addition to the arrangements made for interrupting the flow of current in the controller, it is necessary to have some protection against overload caused by accelerating the car too rapidly, or by a fault developing on the equipment. To do this it is standard practice to fit two circuit breakers, one at each driving position, these being connected in series between the trolley and the line terminal of the controller. Typical circuit breakers are illustrated in Fig. 56. The main power contacts are located in an arc chute and arc rupture is assisted by means of a blowout coil, which is also used to actuate the overload tripping mechanism. A fixed handle is fitted which returns to the normal "off" position whether opened by hand or tripped due to over-

FIG. 56a.—CIRCUIT BREAKER

(English Electric

load. A calibration plate is fitted giving a wide range of tripping values to suit various working conditions, means of easy adjustment being provided.

STARTING RESISTANCES

A wide variety of these are available, examples being illustrated in Fig. 57. The resistance may be built up from either cast iron grids, pressed splayed grids, expanded metal grids or bent strip grids, the three latter types being unbreakable. The grids are mounted on rods or bars insulated with mica and spaced by alternate mica and metal washers, these rods are then insulator mounted on to pressed steel end-frames which are supported from the car framework.

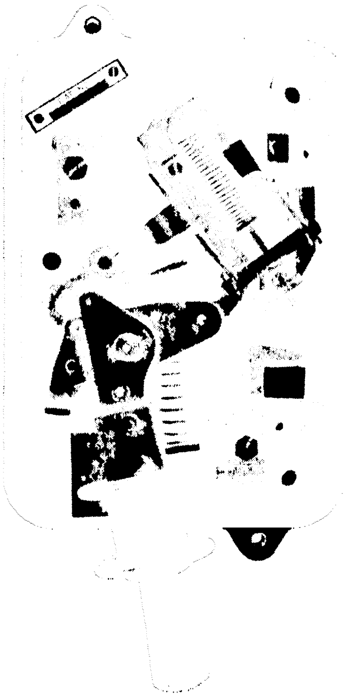


FIG. 56b.—CIRCUIT BREAKER

(*B T.H*)

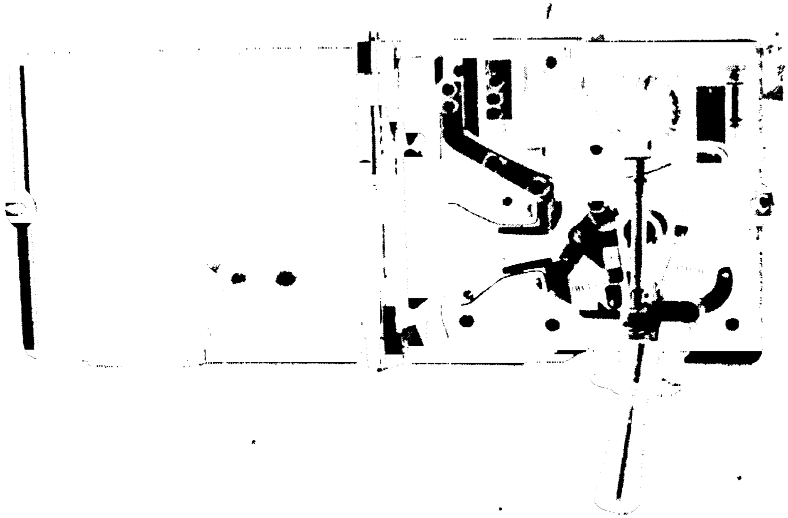


FIG. 56c.—CIRCUIT BREAKER

(*Metro-Vickers*)

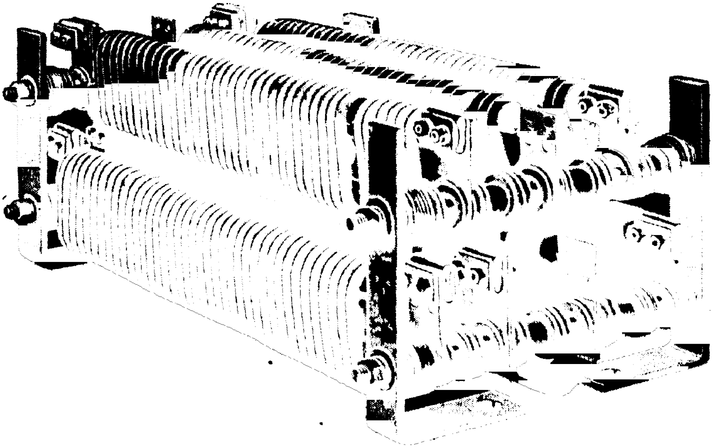


FIG. 57a.—STRIP-WOUND RESISTANCE UNIT

(*B.T.H.*)

TROLLEY-BUS MOTOR CONTROL

In the section on tramway controllers it has been assumed that the controller is hand-operated. However, with a trolley-bus the driver's hands are occupied in steering the vehicle, and control of movement is carried out by pedals as in a petrol or oil-engined omnibus. Two pedals only are used, an accelerating pedal which applies power to the motors, and a braking pedal which operates both electric and pneumatic brakes.

DIRECT CONTROL

There are quite a number of trolley-buses still in operation in the country in which direct control is employed. It is therefore proposed to deal briefly with this type of control before proceeding with modern methods.

The direct controller consists of a modified tramway controller of the cam-operated contact type, mounted horizontally and arranged for operation by pedal. When starting from the "off" position, the accelerating (or power) pedal is depressed to its full extent, this giving the first notch. By returning the pedal halfway and again depressing it, the second notch is obtained. This process is continued up to the full power position, but the controller may be returned to the off position from any notch by

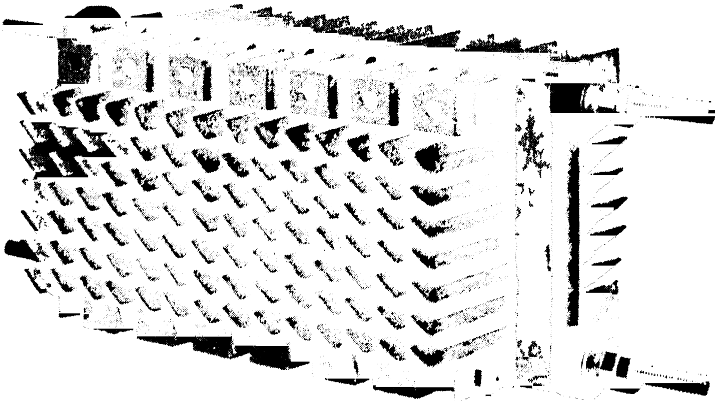


FIG. 57b.—RESISTANCE UNIT (PRESSED SPLAYED GRID)
(*The Rheostatic Co.*)

FIG. 58—CAM-OPERATED TROLLEY-BUS DIRECT CONTROLLER (*English Electric*)

removing all pressure from the pedal. Rheostatic braking is obtained by partial depression of the brake pedal, control of the brake effort being then effected by notching up the power pedal. Full depression of the brake pedal applies the pneumatic brake in addition to the rheostatic. A controller of this type is shown in Fig. 58, it is arranged for series parallel control of the twin armature trolley-bus motor described in chapter two.

INDIRECT CONTROL

All modern trolley-buses are remote controlled by means of contactors, electrically operated from a master controller situated in the driver's cab. Operation of this master controller closes the contactors in a pre-determined sequence and so accelerates the vehicle. Before dealing with systems of control, a description of certain of the component parts will enable the reader to follow the schemes more easily.

MASTER CONTROLLER

This consists of a metal frame carrying control and reverse cylinders. The control cylinder has a number of segments, connected together in groups, which make contact with light fingers mounted on an insulating block, current being supplied to the operating coils of the power and field contactors through these segments and fingers. This system functions in such a manner as to give an effect similar to that of a direct controller, the contactors taking the place of the power segments and fingers. The reverse cylinder is direct in action, carrying the motor current on its segments and their corresponding fingers.

A typical master controller is illustrated in Fig. 59. Its control cylinder rotates through approximately 150 degrees and carries two sets of segments diametrically opposite each other, corresponding rows of fingers being mounted above and below the cylinder itself. This cylinder is rotated by means of a rack

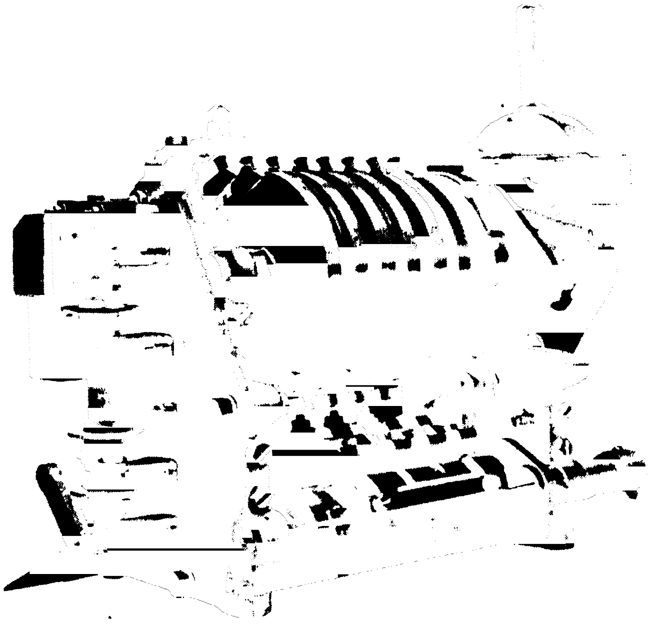


FIG. 59.—TROLLEY-BUS MASTER CONTROLLER

(*English Electric*)

quadrant and pinion, the quadrant being mechanically linked to the accelerating pedal, and the whole system spring-loaded to return to the "off" position. Full depression of the accelerating pedal in this case moves the cylinder through its full amount of travel, no notching being necessary. Situated below the control cylinder is the reversing drum, which is hand-operated by means of the reverse handle mounted at the top of the controller frame, the usual mechanical interlocking between power and reverse operation being provided.

FIG. 60a.—E.M. TROLLEY-BUS CONTACTOR
(*English Electric*)

At the opposite end of the frame to the reverse handle and quadrant is mounted the brake-switch, this consisting of a spindle carrying a series of spring-loaded and separately insulated discs, which make contact in a pre-determined sequence with a number of contacts mounted on the brake-switch panel. This spindle is connected to the brake-pedal and is spring-loaded in the up (or "off") position. In this position, power is supplied to the control cylinder through the uppermost disc and contacts. Pressure on the brake pedal lowers the spindle, first opening the supply to the control cylinder, and then making the brake contactor circuits on the lower three discs.

At the back of the controller frame a panel is mounted, on which are a pair of radio interference suppression coils, one connected in the positive and one in the negative control supply. This modern type of suppression unit, while effective in keeping down interference to a minimum, is small and light in weight. It can be clearly seen on the rear of the controller in Fig. 68b.

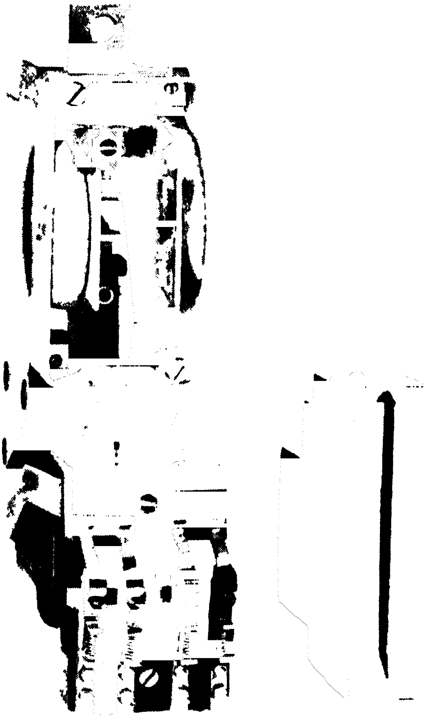


FIG. 60b E.P. TROLLEY-BUS CONTACTOR
(*Metro-Vickers*)

CONTACTORS

Power contactors for trolley-bus work are of two types, electromagnetic and electro-pneumatic; examples of these are illustrated

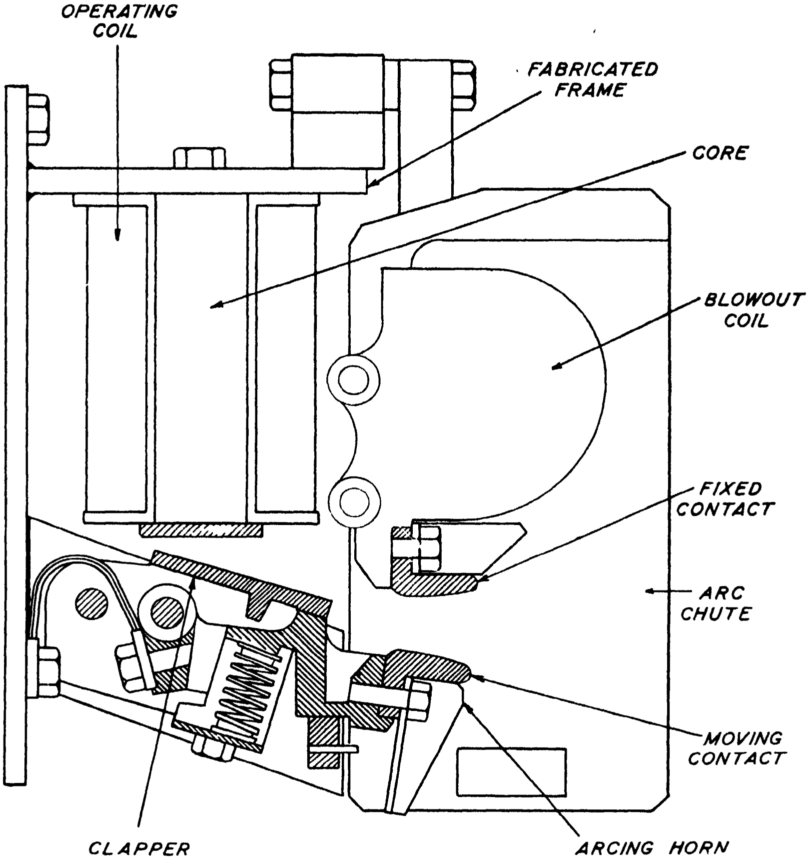


FIG. 61.—DIAGRAMMATIC VIEW OF ELECTRO-MAGNETIC (CLAPPER TYPE) CONTACTOR

in Fig. 60. The diagrammatic view of the former will enable the reader to follow its operation more easily.

The magnet yoke has fastened to it a cylindrical core on which is placed an operating coil wound with several thousand turns of fine gauge insulated wire, and so designed that, when energised continuously on its normal operating voltage, the temperature rise will not exceed 70 to 80° C. Hinged at the lower end of the magnet yoke is a clapper (or armature), which will bed up to the bottom of the core. On energising the operating coil, lines of magnetic force are set up which will pull the clapper up to the

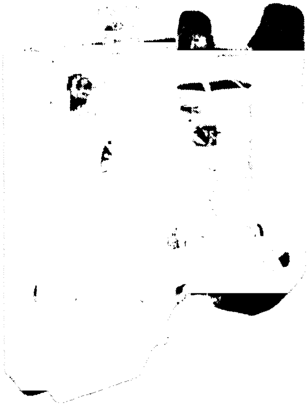
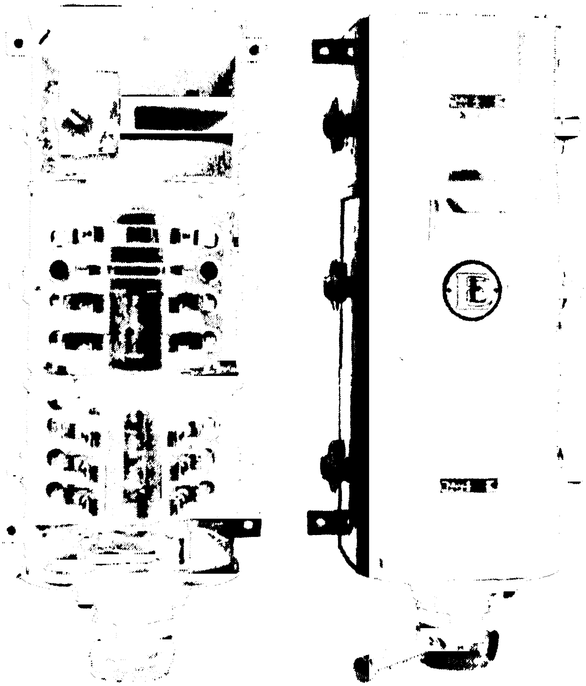


FIG. 62.—SHUNT FIELD CONTACTOR
(*English Electric*)

FIG. 63 (below).—TROLLEY BATTERY CHANGE-OVER SWITCH
(*English Electric*)



core. Fastened to this clapper is the moving power contact, which is so placed that it will just touch the fixed contact when the air-gap between the clapper and the core is $\frac{1}{8}$ in. to $\frac{3}{16}$ in. When the clapper closes up to the core the moving contact arm is pressed back against a spring, and hence the necessary contact pressure is obtained. A magnetic blowout coil is fitted in the fixed contact assembly and the contacts themselves enclosed in a arc-chute which carries the blowout pole pieces externally.

With an electro-pneumatic contactor the moving contact is insulator mounted on a piston working in a cylinder, the piston being spring-loaded to keep the contacts in the open position. Compressed air for operating the contactor is admitted into the cylinder on the lower side of the piston under the control of an electro-magnetic valve, which when energised, allows air to pass into the cylinder, thereby raising the piston and closing the main power contacts. On de-energising the valve, the air is cut off and the cylinder exhausted to atmosphere, allowing the piston to

FIG. 64—OVERLOAD RELAY

(*Metro-Vickers*)

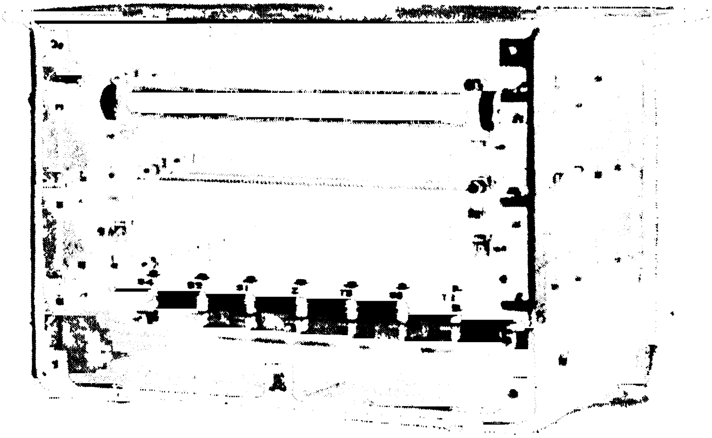


FIG. 65.—SHUNT FIELD RESISTANCE UNIT

(Metro-Vickers)

return under its spring-loading and so opening the main contacts. The fixed contact and blowout assembly is similar to that for an electro-magnetic contactor.

Shunt field contactors are constructed on similar lines to an electro-magnetic power contactor but are smaller in size. The contactor shown in Fig. 62 is capable of rupturing highly inductive field currents, and embodies a unique feature in the inclusion of the whole blowout coil and fixed contact assembly in the arc-chute.

TROLLEY-BATTERY SWITCH

To obtain emergency manœuvring of the vehicle round road obstructions etc., power may be obtained from the lighting battery by the fitting of a trolley-battery changeover switch. This consists of a two-position switch incorporating a foot controlled electromagnetic contactor. The changeover switch, which is of the drum type with fixed fingers, has two functions; the first is to put the two halves of the battery in series in order to get a reasonable voltage for battery manœuvring, at the same time disconnecting the trolleys from the equipment. Secondly, to arrange the two halves of the battery in parallel for charging and

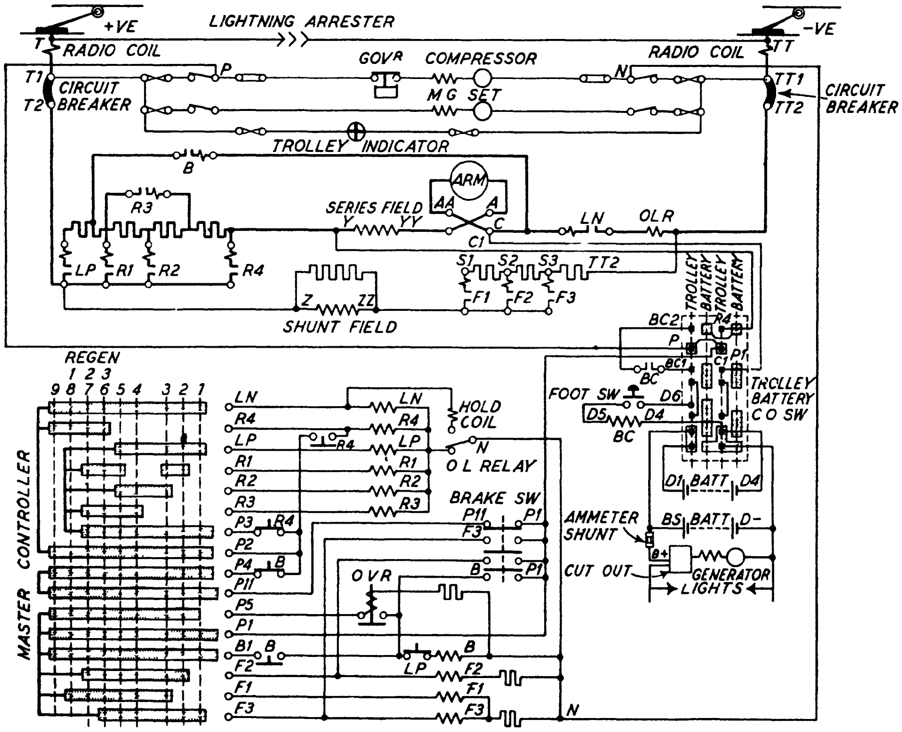


FIG. 66.—REGENERATIVE CONTROL SCHEME

NOTCH		LP	LN	R1	R2	R3	R4	F1	F2	F3	B
		CONTACTORS									
OFF											
POWER	1	●	●							●	
	2	●	●	●					●	●	
	3	●	●	●	●			●	●	●	
	4	●	●		●	●		●	●	●	
	5	●	●	●	●	●		●	●	●	
	6		●				●	●	●	●	
	7		●				●	●	●		
	8		●				●	●			
	9		●				●				
REGEN	1		●				●	●			
	2		●				●	●	●		
	3		●				●	●	●	●	

MASTER CONTROLLER

NOTCH		LP	LN	R1	R2	R3	R4	F1	F2	F3	B
RHEO	1								●		●
	2								●	●	●

BRAKE SW

(English Electric)

normal purposes. This changeover switch, illustrated in Fig. 63, is operated by the reverse handle to provide interlocking with the controller. The contactor, which is remote controlled from the battery by means of a foot pedal switch, is used to apply battery volts to the traction motor.

OVERLOAD RELAY

This relay consists of a coil of several turns inserted in the main power circuit which, on the line current reaching a certain value, attracts an armature carrying contact fingers. These fingers on breaking contact cause the main power contactors to open and, by means of a "hold" coil, prevent them from being closed again until the master controller has been returned to the "off" position. A typical overload relay is shown in Fig. 64.

SHUNT FIELD RESISTANCE

A shunt field resistance is used in the shunt field circuit of the main motor. It has tappings for obtaining various values of field current, and includes a discharge resistance, connected across the motor shunt field, to reduce the arcing at the shunt field contactors.

RHEOSTATIC BRAKING

Rheostatic braking is obtained by loading the motor armature across a portion of the starting resistance, the shunt field being excited with a variable field current to control the braking torque.

REGENERATIVE BRAKING

Regenerative braking can only be employed when the motor is running on a weak field notch, and is obtained by the application of shunt field excitation thereby causing the back e.m.f. of the motor to rise above the line voltage and so return energy to the line.

OVER-VOLTAGE RELAY

When regenerative braking is to be used, an over-voltage relay is usually fitted. This is a relay which, on the line voltage rising approximately 20 per cent, isolates the motor from the overhead line and then closes the rheostatic brake contactors.

RUNBACK AND COASTING BRAKES

Two special features which are often incorporated in trolley-bus control schemes when the bus is for use in a hilly district are the runback and coasting brakes. The former consists of a nor-

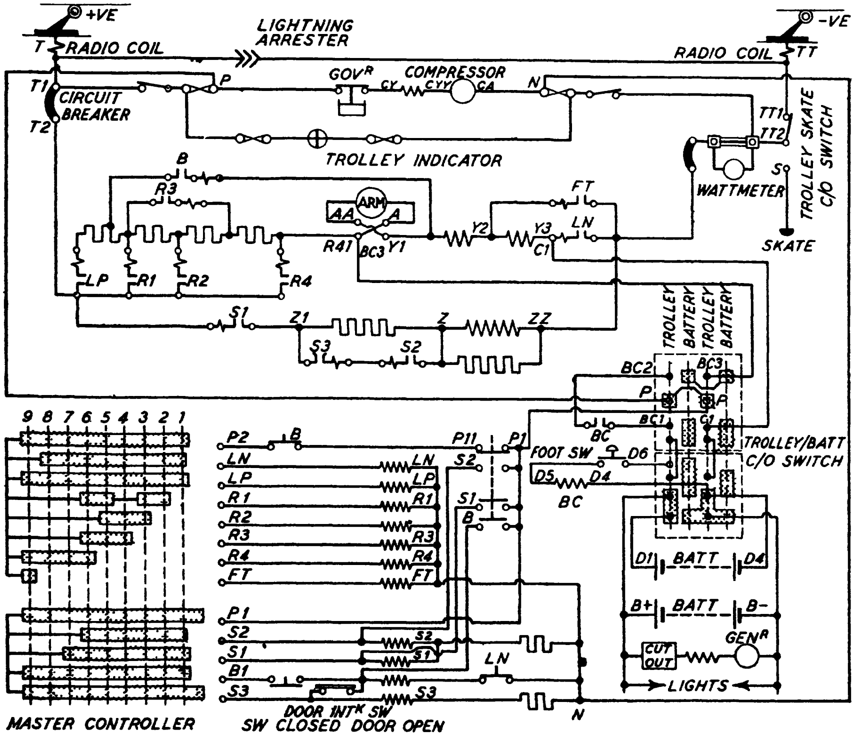


FIG. 67.—SERIES-DYNAMIC CONTROL SCHEME

MASTER CONTROLLER

NOTCH			LN	LP	R1	R2	R3	R4	FT	S1	S2	B
OFF												
POWER	FULL FIELD	1	●	●						●	●	
		2	●	●	●					●	●	
		3	●	●	●	●				●	●	
		4	●	●		●	●			●	●	
		5	●	●	●	●	●			●	●	
		6	●	●	●		●	●		●	●	
	W FIELD	7	●	●				●		●		
		8	●	●				●				
		9	●	●				●	●			

BRAKE SW

NOTCH		LN	LP	R1	R2	R3	R4	FT	S1	S2	B
RHEO	1								●		●
	2								●	●	●

NOTE - S3 CONTACTOR OPERATES ON OVER-VOLTAGE ONLY

(English Electric)

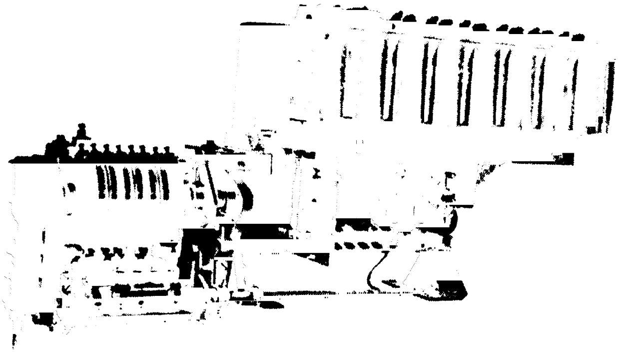


FIG. 68a—FRONT VIEW MASTER CONTROLLER AND CONTACTOR PANEL FOR CAB MOUNTING

(English Electric)

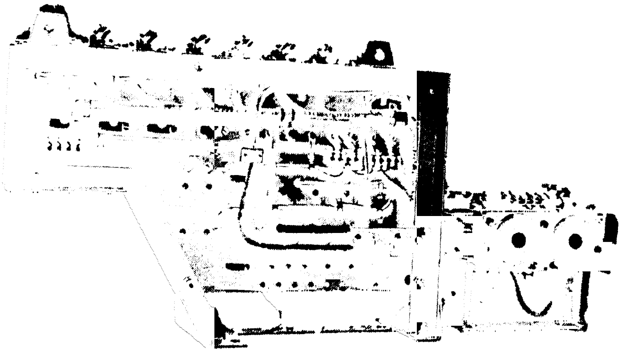


FIG. 68b—REAR VIEW MASTER CONTROLLER AND CONTACTOR PANEL FOR CAB MOUNTING

(English Electric)

mally closed contactor which short-circuits the motor in the off position as in tramway runback brakes. The latter is obtained by an extra position on the reverse drum which connects the motor armature and series field in such a way that it will function as a generator. This is then loaded with a portion of the starting resistance, and hence will limit the speed of the vehicle.

OPERATION SCHEMES

A schematic diagram of connections for a trolley-bus fitted with regenerative control, trolley-battery changeover switch, overload and overvoltage relays and a motor-generator lighting set is shown in Fig. 66. The development of the master controller cylinder with the dotted indication of the notch positions, together with the power chart of the contactors, will assist the reader to follow out the sequence for power. For regenerative braking the power chart is reversed back from notch 12 to notch

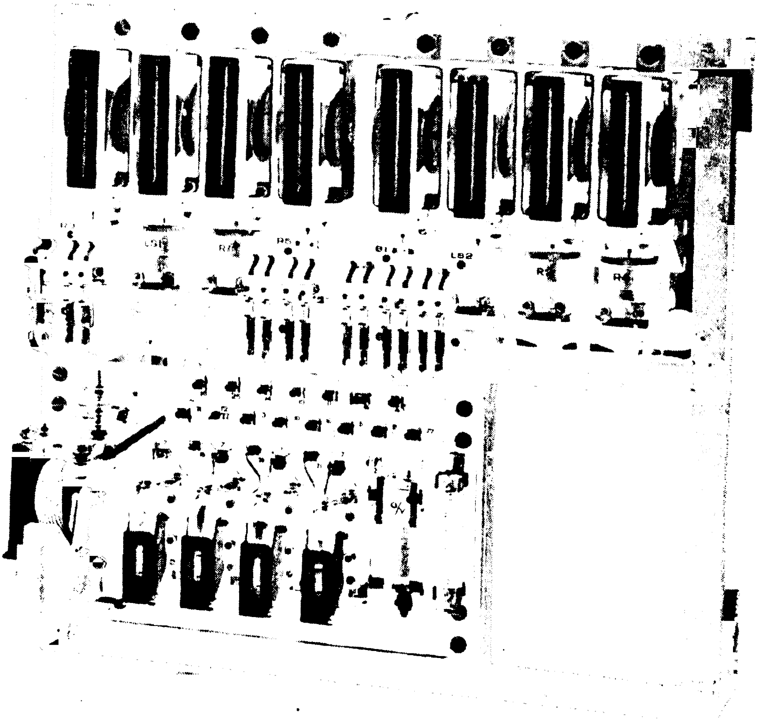


FIG. 69.—E.P. CONTACTOR PANEL WITH RUN-BACK CONTACTOR

(*Metro-Vickers*)

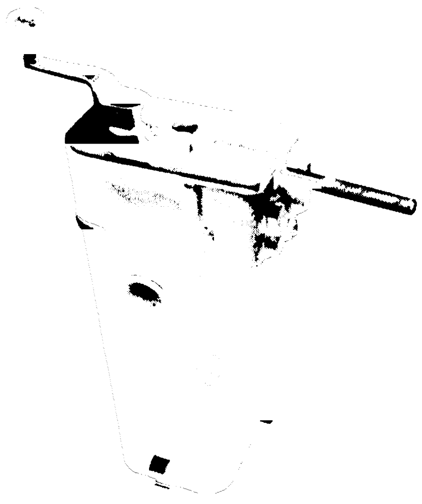


FIG. 70.—TRAMWAY MASTER CONTROLLER (B.I.H.)

9, this giving full regenerative brake. For rheostatic braking a separate smaller power chart is included, the two brake notches being obtained by slowly lowering the brake switch spindle.

Another type of connection scheme is shown in Fig. 67. In this, the motor has a tapped series field and a much weaker shunt field. No overload relay is provided, the main circuit breakers being relied upon for protection. Overvoltage protection is obtained by means of a shunt field contactor, which opens circuit when its coil is energised at more than 20 per cent above line voltage, and by doing so, inserts a resistance in the motor shunt field circuit with a consequent reduction in the regenerated voltage. Development and power charts are given and it will be noted that only nine power notches are used against twelve notches in the previous scheme. Low tension lighting in this case is provided by means of a generator driven from the main motor.

Contactor groups may be made up in two ways. All the contactors and relays may be mounted on a panel which fits into the driver's cab alongside the master controller (Fig. 68).

Alternatively they may be placed in two chassis-mounting cases, one containing the power contactors and the other the shunt field contactors and relays together with the shunt field resistance. Examples of the mounting of these types of equipment are given in the chapter on Rolling Stock.

Contactor control, indirectly operated has been applied in recent years to tramways. The master controller is hand-operated, the actual control scheme being similar to that for an indirectly controlled non-multiple unit motor coach without automatic acceleration, for details of which the reader is referred to the following chapter.

Chapter 4

THE CONTROL OF RAILWAY MOTORS

THE control of railway motors may be treated in two separate sections, viz., Motor coach applications where the equipment is for urban and suburban work; and Locomotives, these being independent power units which may be used to haul any type of train within their capacity.

MOTOR COACHES

Motor coaches may be controlled by two methods: direct control as in a tramcar, and indirect control in which are included all systems where the actual control of the motors is remote from the driving position.

DIRECT CONTROL

This system is now almost obsolete. It was used in the early days of the electric train and consisted of a series-parallel controller of the drum type, as outlined in the previous chapter, built on a larger scale. This method had the disadvantage that only the motors actually fitted to the motor-coach in which the controller was situated could be controlled, and as a result, several schemes were introduced for operating an additional motor coach at the rear of the train. This was accomplished by duplication of all starting resistances at each end of the train, fitting extra segments and fingers on the controller to control the distant motors, and employing a remote-controlled reverser. As many difficulties were encountered with this type of control, it was soon superceded by the various methods of indirect control with multiple-unit operation.

INDIRECT CONTROL WITH MULTIPLE-UNIT OPERATION

There are three different systems of indirect control, viz. electro-magnetic, electro-pneumatic, and camshaft controller. Many of the components employed are exactly the same for all systems, e.g. the master controller, overload relays, no-current relays, cut-out and isolating switches and fusegear. Others such as the reverser and contactors, while having a similar function, differ in their construction and method of operation. It is therefore proposed to deal with each system in rotation, and give details where necessary of the various components.

ELECTRO-MAGNETIC CONTROL

For this type of control the equipment required for one motor-coach is as follows; master controller, main starting resistance boxes, contactors including line-breakers, reverser, overload and no-current relays, isolating switch, cut-out switches and fuses. In addition, a field tapping switch, additional circuit-breakers, and a current limit relay may be fitted. A power train-line runs throughout the length of the train in order that power may be supplied to the motor coach in the event of its own collector shoes being in an isolated or " dead " section. The use of a multiple-way control train-line enables one master controller to operate all motor-coach units throughout the train.

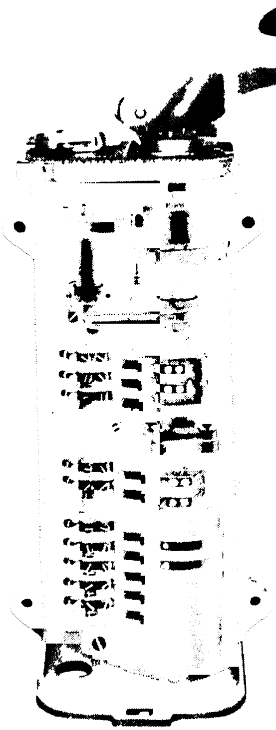


FIG. 71a.—RAILWAY MASTER CONTROLLER (*Metro-Vickers*)

THE MASTER CONTROLLER

The master controller has two cylinders; a reverse cylinder, master key operated, which controls all the reversers on the train, and a control cylinder operated by a handle in a similar manner to the tramway controller power cylinder. The segments and fingers are small as they only have to transmit and rupture the control circuit currents which are about one to two amperes. Blowout arrangements are sometimes fitted when the control voltage is of the order of 500 volts, this however is now the exception, as low-voltage control at 50 to 150 volts is becoming increasingly popular.

To ensure that the driver is actually in control of the train, a "dead man's handle" is incorporated in the main control handle, and it is necessary for a pressure to be maintained on it which may be anything from one to seven pounds. Should this pressure be released, one of the following sequences is arranged to occur.

(*a*) A spring-loaded section of the main control cylinder is released and breaks contact with its fingers, so opening the control circuit supply.

(*b*) An air pressure switch is employed, through which the control circuits are supplied. Release of the dead man's handle allows air to escape and in consequence the pressure switch opens, this system being easily arranged to give a brief time delay if necessary.

In addition, the dead man's handle is also coupled to the train braking system, so that besides cutting off the power supply, the brakes of the train are applied to bring it to rest.

Typical examples of master controllers are shown in Fig. 71.

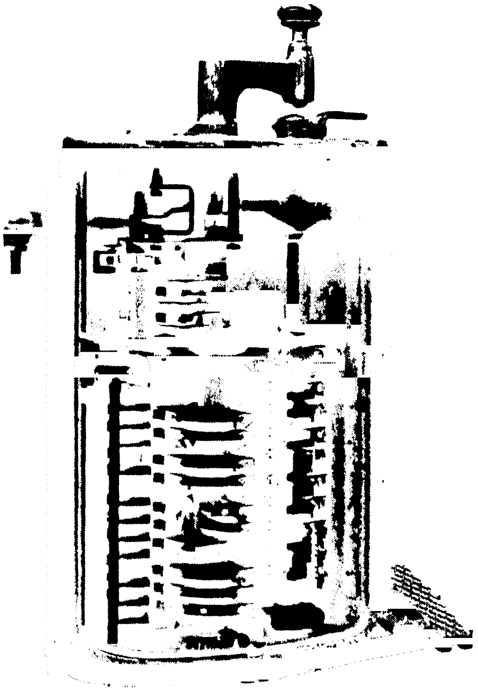


FIG. 71b.—RAILWAY MASTER CONTROLLER
(*English Electric*)

FIG. 72a.—ELECTRO-MAGNETIC CONTACTOR
(*English Electric*)

First comes a controller for low-voltage control with a hinged dead man's handle, and incorporating only four running notches. The reverser cylinder is mounted loosely on the main shaft and operated by linkage. Two fingers and segments are mounted in the centre of the shaft, these are the dead man's handle contacts and are of the spring-loaded type.

Secondly comes a low voltage controller with a plunger-type handle which is interlinked with a pedal so that pressure on either indicates that the driver is in control of the train. Note the hinged spark barrier which encloses the contact fingers.

CONTACTORS

An electro-magnetic contactor for railway work is similar in general outline to the one used in trolley-bus work but larger and more robust. Two such contactors are shown in Fig. 72, the latter having its moving contact carried on a plunger instead of a clapper. When it is desired to close the power contacts, the iron-cored operating coil is energised from the master controller and pulls up the moving armature. The fixed contact assembly has a blowout coil built into it, and the contacts themselves are enclosed in the usual arc-chute. In order to keep the burning of the contacts by the arc from causing high contact resistance between them with consequent overheating, they are arranged to make and break the current at the tips of the contacts, and then as the clapper or plunger moves fully up to the core the moving contact "wipes" or rolls its point of contact over to the rear or "heel"—see Fig. 73.

For control purposes it is frequently necessary to fit interlocks or auxiliary contacts on the contactors, reverser, cut-out switches, etc. These consist of small contacts or fingers which may be

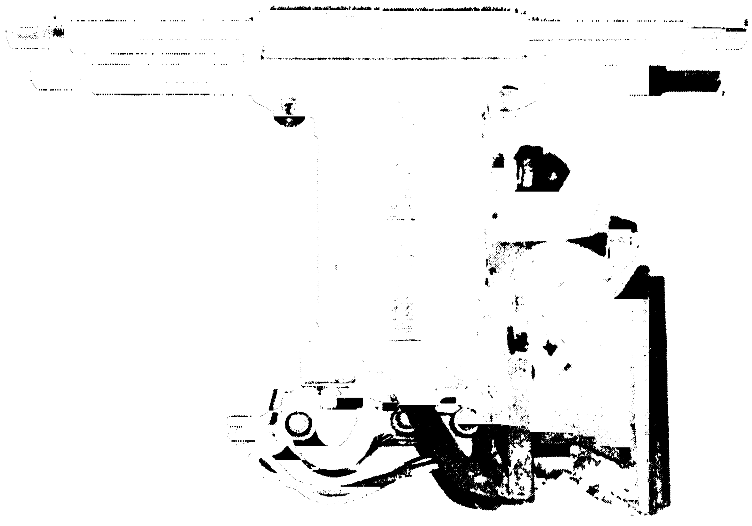


FIG. 72b.—ELECTRO-MAGNETIC CONTACTOR

(*Metro-Vickers*)

open or closed when the main power contacts are closed, and are adjusted and timed to operate at some instant in the travel of the contactor clapper.

MAIN STARTING RESISTANCE

Two types of starting resistances are used in motor-coach equipments, viz.: cast-iron grid and unbreakable pressed-splayed grid. Due, however, to the heavier currents used, much higher ratings are required, and in order to keep the resistance units to a reasonable size for mounting and handling, it is usual to divide the resistance into several separate boxes, two such boxes being shown in Fig. 74.

REVERSER

As a reverser is never operated when current is passing through the traction motors, it is unnecessary to fit its contacts with arc-rupturing arrangements. The reverser consists of a reverse cylinder and fingers similar to those in a direct controller, and is moved from forward to reverse positions and vice versa by two plunger-type electro-magnets energised from the reverse cylinder of the master controller. Interlocks are fitted to the reverser cylinder to ensure that it is in its correct position before any of the power contactors can be operated.

OVERLOAD RELAYS

The essential requirement of an overload relay is that at some pre-determined current it should operate, and by means of its auxiliary contacts cause the main line breakers to open, afterwards locking in the tripped position until reset by a small relay remote-controlled from the driving cab. It consists of an L-shaped magnet yoke carrying an iron core around which are wound several turns of heavy section copper, capable of carrying normal full load current without overheating. Pivoted at one end of the yoke is an armature, so arranged that it is attracted to the core when the field strength between them reaches a pre-determined value. To this armature is attached a spring which pulls in the opposite direction to the magnetic field and it is by adjustment of this spring that the tripping value of the relay may be altered. When the armature moves up to the core the auxiliary contacts which it carries interrupt the control supply to the line breakers which consequently cut off the overload current. Typical overload relays are shown in Fig. 75.

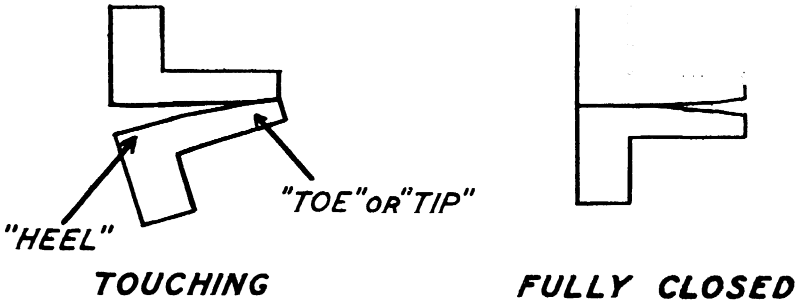


FIG. 73.—WIPING ACTION OF CONTACTS

ISOLATING SWITCH

This switch is used to isolate the whole equipment from the line and consists of a knife switch or some other device for opening the circuit.

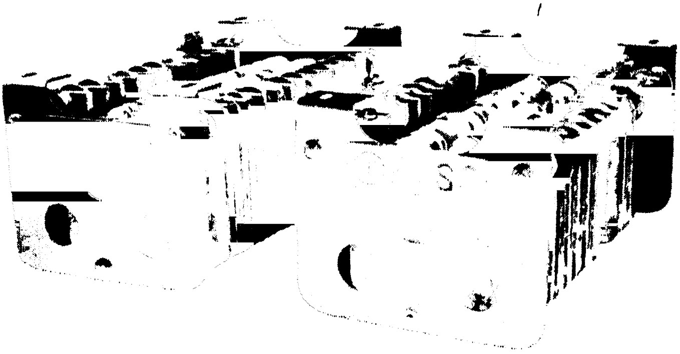


FIG. 74.—CAST-IRON GRID TYPE RESISTANCE BOXES
(English Electric)

CUTOUT SWITCHES

Cutout switches are used to isolate defective motors so that the train may continue to operate. Frequently an assembly similar to a reverser is used but with two drums, one for each motor; hand-operation is employed and interlocks are fitted to make the various adjustments necessary to the control circuit due to the cutting out of one or more motors. The reverser key is used for operating both isolating and cutout switches to ensure that the system is carrying no current when the operation is carried out.

NO-CURRENT RELAY

This relay is similarly constructed to an overload relay, but has more turns on its coil in order that it may operate at very small current values. It is fitted with auxiliary contacts which are closed when the relay picks up, and is used to open the control circuits, and hence the power circuits, in the event of current ceasing to flow due to failure of line volts or to an open-circuit developing in the equipment.

ELECTRO-PNEUMATIC CONTROL

The items of apparatus required for a motor-coach with this type of control are exactly the same as for electro-magnetic control, with the exception that the contactors and reverser are operated by compressed air, admitted and exhausted by means of electro-magnetic valves. A diagram of such a valve is shown in Fig. 78.

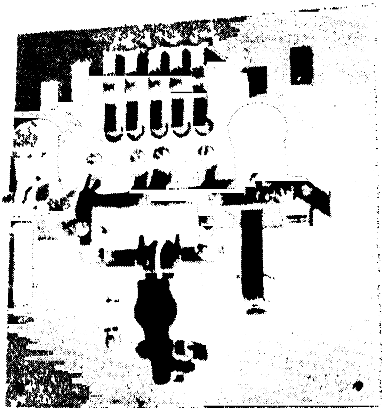


FIG. 75a.—OVERLOAD RELAY

(*English Electric*)

It will be seen that on energising the operating coil, the moving armature is attracted to the core so depressing the valve spindle, closing the exhaust port and admitting compressed air to the cylinder of the contactor or reverser. This state of affairs then continues as long as the coil remains energised. When the current is switched off, the spring in the valve base pushes the spindle and armature up, so sealing off the air supply and releasing the air from the cylinder to atmosphere. The cylinder remains connected to atmosphere while the valve is in this position, so avoiding the possibility of pressure building up in the cylinder due to leakage through the supply valve.

FIG. 75b.—OVERLOAD RELAY

(*English Electric*)

In the case of an electro-pneumatic contactor the moving contact is carried on a piston working in a cylinder; this is spring loaded with the piston in the down position and raised by applying air

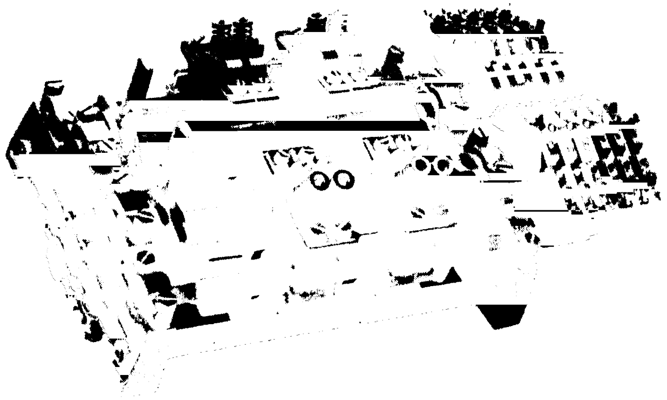


FIG. 76.—MOTOR CUT-OUT SWITCH

(English Electric)

pressure under the piston. A split contactor is shown in Fig. 79a and a light-weight contactor in Fig. 79b.

The reverser consists of a double-acting piston connected to a crank mounted on the reverser cylinder shaft, two valves being fitted, one for each side of the piston to give forward and reverse positions. To obtain either position the appropriate valve is energised, this applies air pressure on the required side of the piston and the reverser moves over. Fig. 80 shows typical reversers of this type. Reversers are also used in which

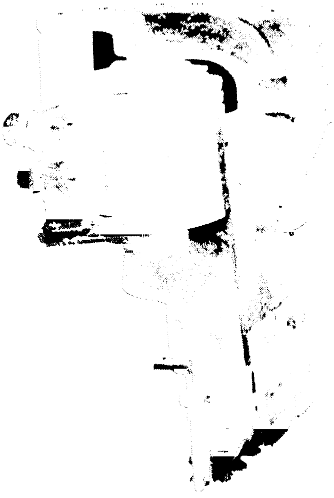


FIG. 77.—NO-CURRENT RELAY

(English Electric)

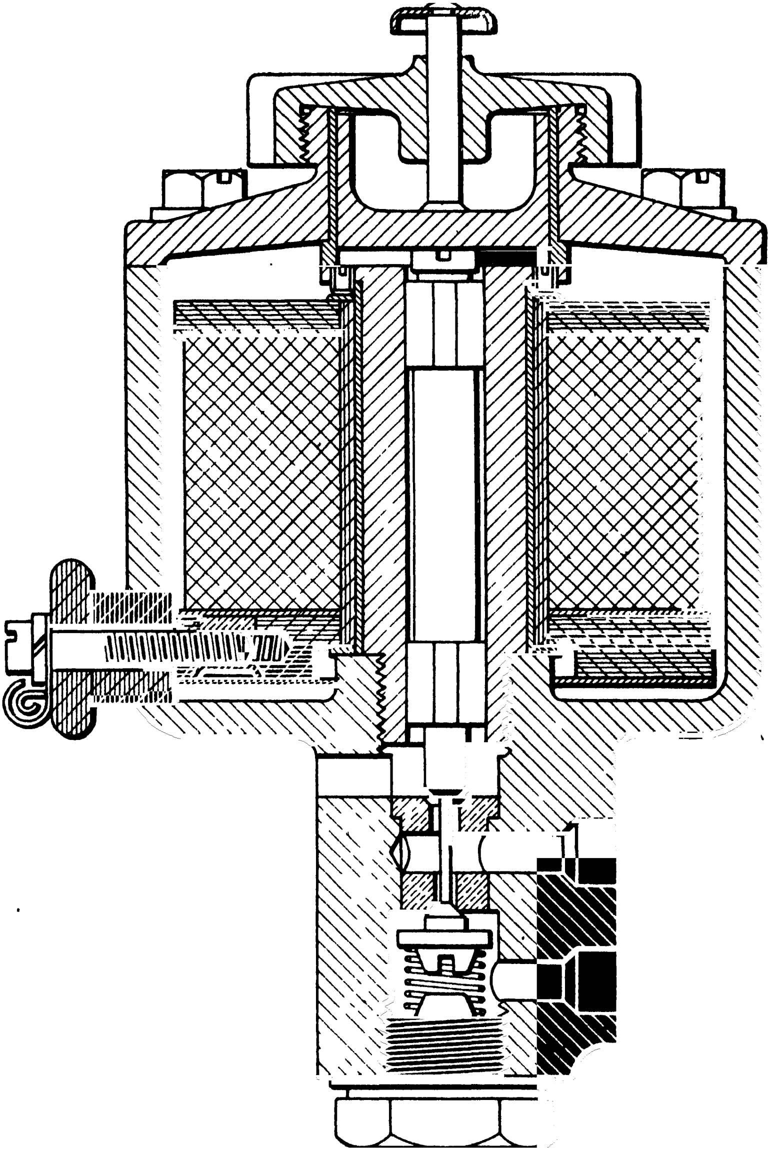


FIG. 78.—DIAGRAMMATIC SECTION THROUGH ELECTRO-MAGNETIC AIR VALVE
(*Metro-Vickers*)

cam-operated contacts are employed instead of the segments and fingers, in which case the camshaft is moved by means of the air-piston.

FIELD TAPPING

Two methods are used for changing from one tapping to another while power is on the motors. A cam-operated change-over switch may be employed, this being similar to the cam-operated reverser described in the previous paragraph, with the addition of blowout arrangements and arc-chutes for all contacts. The cams are timed so that the sets of contacts overlap each other thereby ensuring that the motor circuits are not broken during tap-changing. The alternative method is by using separate contactors,

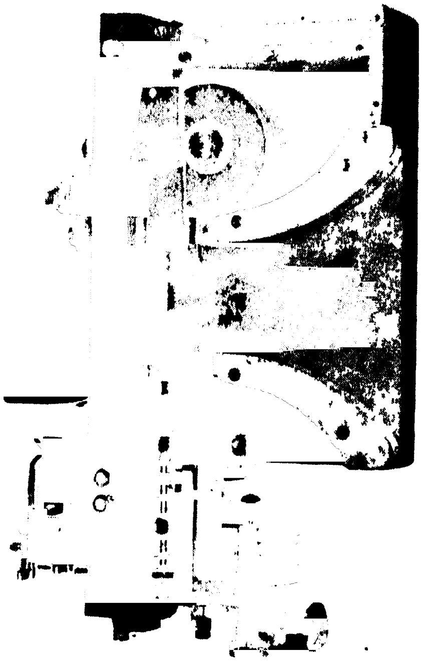


FIG. 79a.—SPLIT E.P. CONTACTOR

(*Metro-Vickers*)

in which case auxiliary contacts are used as interlocks to ensure the necessary overlap.

NON-AUTOMATIC CONTROL

A simplified typical non-automatic control and power scheme is shown in Fig. 82. Bridge transition is employed, and arrangements are included for cutting out a defective motor. The contactors are operated by energising their operating coils from

FIG. 79b.—LIGHTWEIGHT E.P. CONTACTOR
(*English Electric*)

the master controller through its segments and fingers. To prevent faulty operation, a number of interlocks are provided to ensure that:

(*a*) When a motor is cut-out, the sequence cannot proceed beyond normal full series in which position the motor in use has full line volts applied to it.

(*b*) Contactors *LS*1 and *G* cannot close until *JR* is opened.

(*c*) Contactor *JR* cannot close unless *G* is open.

(*d*) The overload relay trips out the line-breakers *LB*1 and *LS*1.

(*e*) Note also that no contactors can be operated until the reverser has thrown to either of its positions, the auxiliary contacts not making circuit until the reverser main contacts are fully closed.

(*f*) The overload relay can only be reset in the "off" position.

With the assistance of the power chart, the reader should have no difficulty in following the sequence which is as follows. The control switch is first moved to the "reset" position in order to restore to normal any overload relays which may be in the tripped position. It is then set to "control", the reverser key fitted in its appropriate position on the controller and moved to the direction required, this throwing the reverser to its correct position. Proceeding notch by notch through the sequence starting from the "off" position, notch 1 brings in *LB*1 and *JR* contactors only. Notches 2 to 7 close the six resistance contactors one by one. Notch 8 puts the motors in direct series by closing contactor *J*, at the same time opening *JR* and the six resistance contactors and so preparing the circuit for transition by the bridge method. On moving to the next notch (i.e. 1st parallel) contactors *LS*1 and *G* close, then *J* opens, the arcing on its contacts being reduced by suitable presetting of the starting resistance to such a value that the current passing through contactor *J* is very small. Continuing, the resistance is again cut out step by step until the full parallel position is reached.

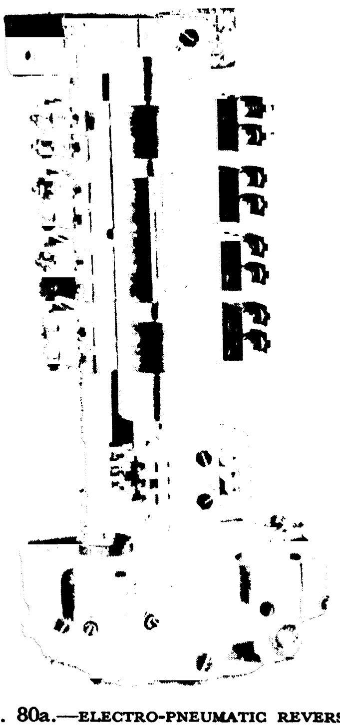


FIG. 80a.—ELECTRO-PNEUMATIC REVERSER (*Metro-Vickers*)

MULTIPLE-UNIT OPERATION

When used for multiple-unit operation, all the leads passing from the master controller into the train-line are connected to the various equipments in the train, so that they run through the sequence concurrently. One point about the connecting of reverser control wires is very important. Controllers which have forward and reverse positions in the opposite sense, due to being at the rear of the train, must have the connections to the forward and reverse fingers crossed, or alternatively they must be crossed in the train-line itself. This is because forward to the leading controller on the train is reverse to the trailing end controller.

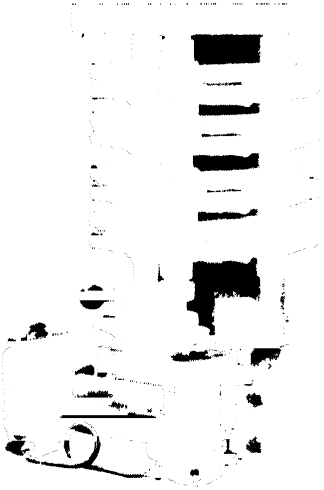


FIG. 80b.—LIGHTWEIGHT E.P. CYLINDER TYPE REVERSER
(*English Electric*)

AUTOMATIC CONTROL

With this type of control the actual notching up is controlled by an accelerating or "current limit relay", the master controller drum having only first series, full series and full parallel notches together with field-tap notches if fitted. The controller handle is

FIG 81a.—FRONT VIEW CONTACTOR GROUP CASE FOR UNDERFRAME MOUNTING
(*English Electric*

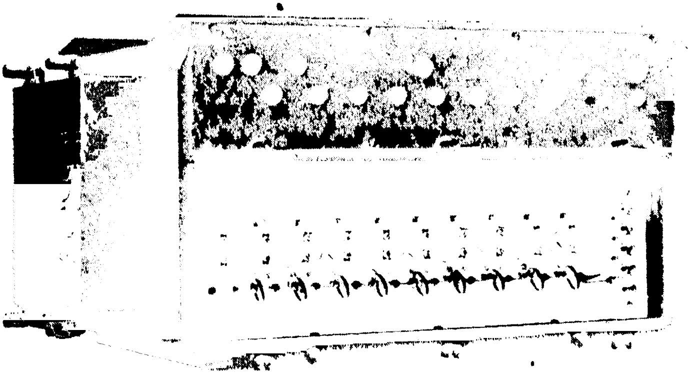


FIG. 81b.—REAR VIEW. CONTACTOR GROUP CASE FOR UNDERFRAME MOUNTING
(*English Electric*)

moved to whichever of these positions is required, and the resistance is then cut out step by step automatically, transition follows and the process repeats itself.

CURRENT LIMIT RELAY

The current limit relay consists of a magnet yoke and core, the main power current being carried round a copper coil of several turns mounted on the core. The pivoted armature or plunger is spring-loaded in the out position; when the current reaches a pre-determined value, this armature moves a certain distance towards the core, its travel being limited by a stop, and on the current falling to another set value, the armature drops back again. Adjustment of these "pick up" and "drop-off" values is obtained by varying the spring-tension and the gap between armature and core, and by this means it is possible to get the pick up and drop off values within 10 per cent of each other. Mounted on the armature or plunger are a pair of auxiliary contacts which break contact when the rising current draws the armature towards the core. Typical current limit relays of the pivoted armature

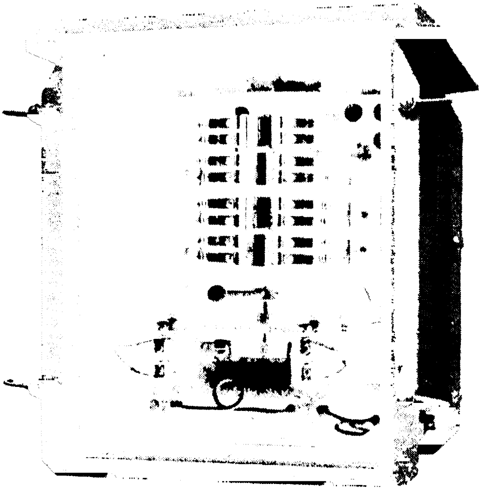
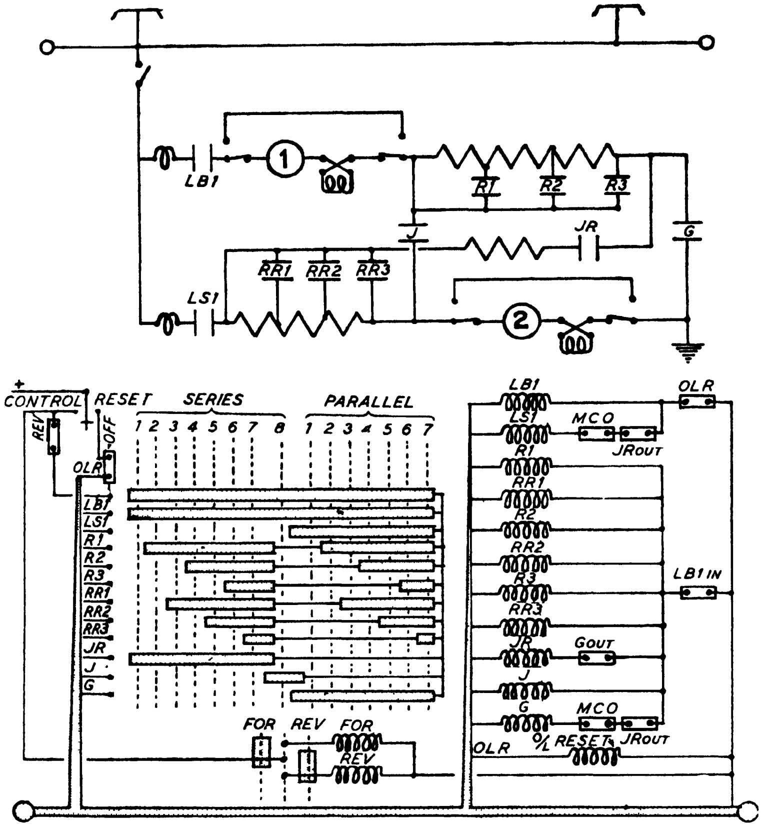


FIG. 81C - REVERSER CASE FOR UNDERFRAME MOUNTING
(*English Electric*)



		LB1	LS1	R1	R2	R3	RR1	RR2	RR3	J	JR	G
SERIES	OFF											
	1	●									●	
	2	●		●							●	
	3	●		●			●				●	
	4	●		●	●		●				●	
	5	●		●	●		●	●			●	
	6	●		●	●	●	●	●			●	
	7	●		●	●	●	●	●	●		●	
	8	●								●		
TRANSITION		●	●							●		●
PARALLEL	1	●	●									●
	2	●	●	●								●
	3	●	●	●			●					●
	4	●	●	●	●		●					●
	5	●	●	●	●		●	●				●
	6	●	●	●	●	●	●	●				●
	7	●	●	●	●	●	●	●	●			●

FIG. 82.—NON-AUTOMATIC CONTROL

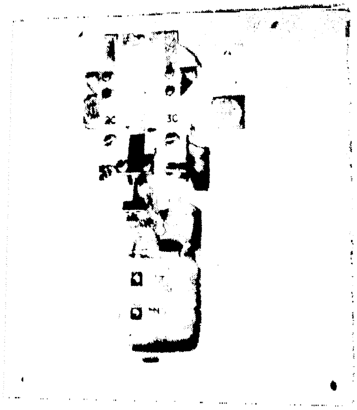


FIG. 83a.—PIVOTED ARMATURE TYPE CURRENT LIMIT RELAY
(*English Electric*)

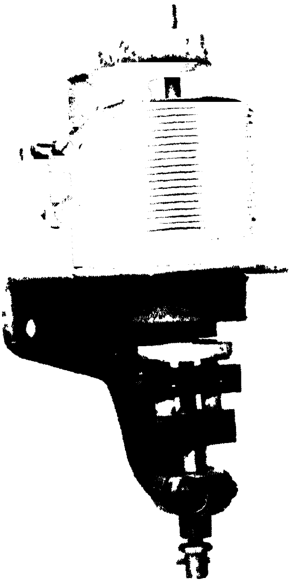


FIG. 83b.—PLUNGER TYPE CURRENT LIMIT RELAY
(*English Electric*)

and plunger types are shown in Fig. 83, and it will be noted that the former has a shunt coil electro-magnetic unit fitted underneath, energising of which increases the spring tension on the main armature, thereby raising the pick up and drop off values.

AUTOMATIC ACCELERATION

In order to enable the reader to follow the principle of automatic acceleration, a simple scheme for the acceleration of a single motor with four resistance contactors and a current limit relay is

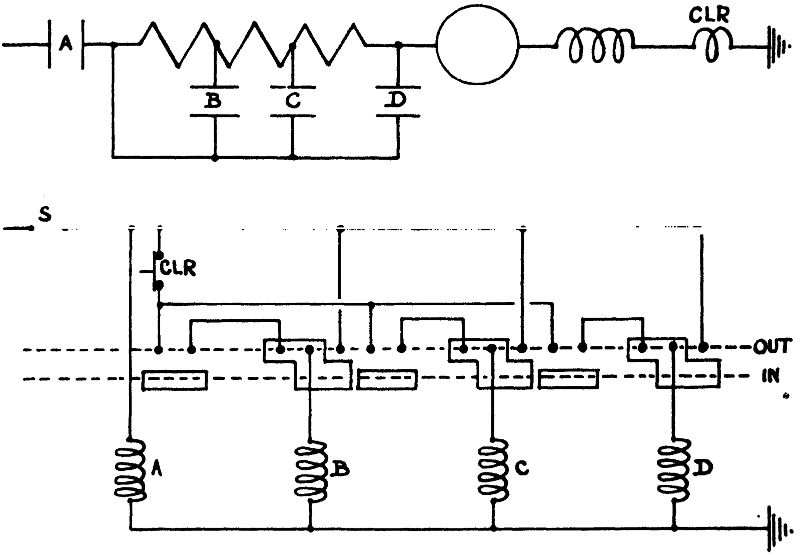


FIG. 84.—SIMPLE AUTOMATIC ACCELERATION SCHEME FOR ONE MOTOR

shown in Fig. 84. On referring to the diagram, it will be noted that each contactor operating coil is energised first through a "pick up" or "actuating" wire, and then by means of its interlocks transfers this feed to a retaining wire. To start the motor, switch *S* is closed, this picks up contactor *A*. On this contactor is an interlock which closes after the main power contacts have closed, this interlock connects the pick up wire of contactor *B* to the supply through the current limit relay auxiliary contacts. However the peak current caused by contactor *A* closing will have picked up the current limit relay, and hence the actuating circuit of contactor *B* is interrupted at the relay auxiliary contacts. When the current has fallen to the set value, the current limit

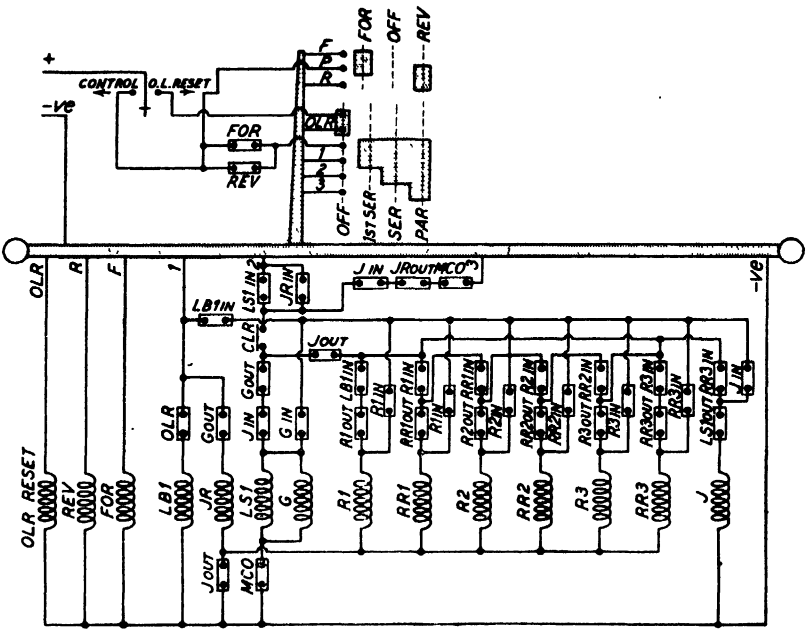


FIG. 85.—CONTROL CIRCUITS FOR AUTOMATIC ACCELERATION OF POWER SCHEME SHOWN IN FIG. 82

relay will drop out, the actuating circuit of contactor *B* will be made, *B* will close transferring its operating coil feed to the retaining wire, and by short-circuiting some of the resistance will further accelerate the motor. The same sequence is again repeated using the interlocks on contactors *B* and *C* to close *C* when the main current has again fallen to the set value of the current limit relay, and similarly with contactor *D*. This illustrates the simple principle of automatic acceleration, and its application to the control circuit of the two-motor equipment of Fig. 82 is shown in Fig. 85.

It will be noted that the controller is considerably simplified by the reduction of the number of notches from 15 to 3. The interlocks are shown by the system in which the wording (e.g. *R*1 in) refers to the position of the contactor when the auxiliary contacts are closed. Several additional interlocks are fitted in order to obtain transition together with series-parallel sequence.

The reverser operates as previously on movement of the reverse key, and has auxiliary contacts in the supply circuit to the master controller control cylinder to ensure that the reverser is in its correct position before current can be supplied to the traction motors. On moving the controller to the "first series" notch, contactors *LB*1, *JR* close, and connect the motors and starting resistances all in series. Movement to the second or "series" notch energises the current limit relay circuit through wire 2 and "*JR* in" interlock, and the sequence proceeds up to full series under control of the relay. The last step in this sequence closes contactor *J* and drops out all the resistance contactors together with *JR*, so preparing the circuit for transition. Due to the opening of *JR*, the feed from wire 2 to the current limit relay is interrupted, and the system will stay in this position until the master controller is moved to the third or "parallel" notch, which again energises the current limit relay from wire 3 through "*J* in", "*JR* out" and "*MCO*" interlocks, so closing contactors *LS*1 and *G*. The closing of *LS*1 drops out *J* by means of the "*LS*1 out" interlock and so completes transition. The sequence then proceeds to full parallel, the actuating circuits being again fed from wire 2 through the "*LS*1 in" interlock.

FIG. 86 POSITION RELAY
(English Electric)

CAMSHAFT CONTROL EQUIPMENT

Hand operated camshaft controllers of the type described in Chapter 3, are sometimes used on light motor-coach work where multiple-unit working is not required. As however, modern tendency is towards standardisation of multiple-unit equipment, two types of camshaft controller have been developed suitable for both automatic and non-automatic control. The equipment required with these systems is identical with that for electro-magnetic and electro-pneumatic contactor control, with the exception that all the contactors, except in some cases the line-breakers, are cam-operated and form a part of the main camshaft controller assembly.

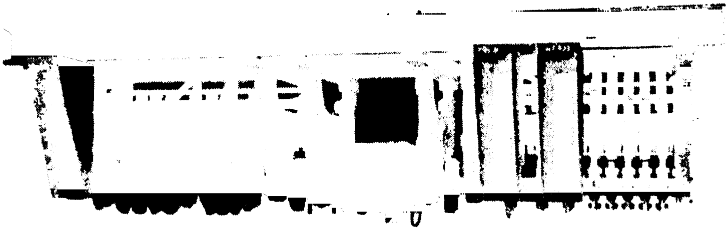


FIG. 87a.—FRONT VIEW: MOTOR OPERATED CAMSHAFT

(*English Electric*)

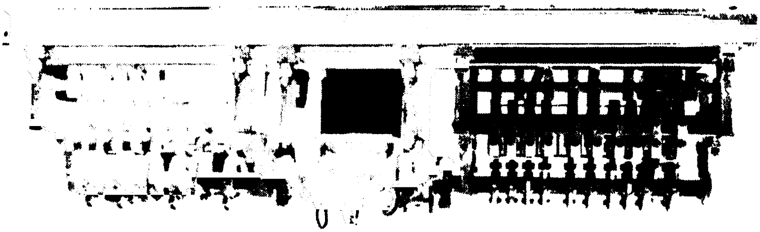
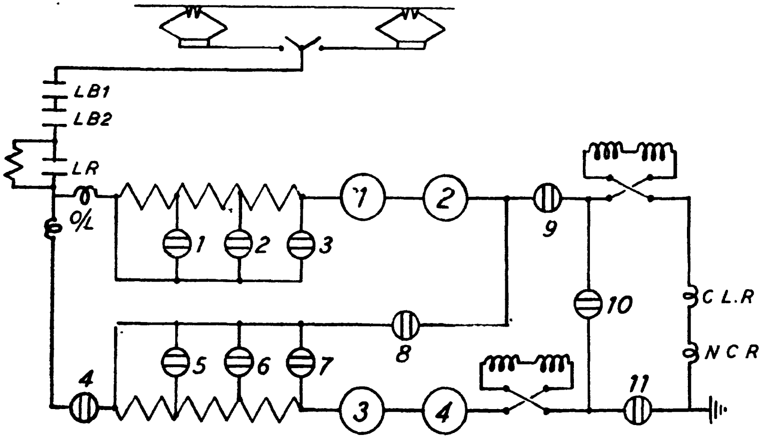


FIG. 87b.—REAR VIEW: MOTOR OPERATED CAMSHAFT

(*English Electric*)

ALL-ELECTRIC CAMSHAFT CONTROL

With this system the contactors with the exception of the line-breakers are cam-operated, the camshaft itself being worm



⊣⊢ DENOTES E.P. CONTACTOR

⊖ DENOTES CAM-OPERATED CONTACTOR

		LB1	LB2	LR	1	2	3	4	5	6	7	8	9	10	11
OFF		■	■	■	■	■	■	■	■	■	■	○	■	○	■
SERIES	1	○	○	○	■	■	■	■	■	■	■	○	■	○	■
	2	○	○	○	○	■	■	■	■	■	■	○	■	○	■
	3	○	○	○	○	○	■	■	○	■	■	○	■	○	■
	4	○	○	○	○	○	○	■	○	○	■	○	■	○	■
	5	○	○	○	○	○	○	■	○	○	○	○	■	○	■
TRANSITION		○	○	○	○	■	■	■	■	■	■	○	■	○	■
		○	○	○	○	■	■	■	■	■	■	○	○	○	■
		○	○	○	○	■	■	■	■	■	■	■	○	■	■
PARL	6	○	○	○	○	■	■	○	○	■	■	■	○	■	○
	7	○	○	○	○	○	■	○	○	○	■	■	○	■	○
	8	○	○	○	○	○	○	○	○	○	○	■	○	■	○

FIG. 88a.—ALL-ELECTRIC CAMSHAFT POWER CIRCUITS

driven by a small shunt motor of about one-half horse-power. By a series of interlocks on the line-breakers which form the reversing contacts for this motor, the cam-shaft can only be advanced when the line-breaker is closed and returned after the line-breaker has opened. By this means all the arc rupturing is confined to the line-breakers, with the exception of that on certain contactors during transition, and consequently the fitting of magnetic blowouts and arc chutes is avoided on most of the contactors. The actual movement of the camshaft motor armature is controlled by the camshaft motor relay, which when energised supplies power to the motor, and when de-energised short-circuits the motor armature to stop it quickly. The operation of this cam-motor relay is controlled by the position regulator on the camshaft and by the position relays, these being simple relays whose operating coils are energised as required from the control cylinder of the master controller. Figures 86, 87 show a position relay and a complete camshaft controller respectively.

Typical camshaft operated motor-coach power and control circuits are shown in Fig. 88. The arrangement is for a 1500 volt system employing four motors, each pair of which are connected in permanent series. Shunt transition is employed, and the

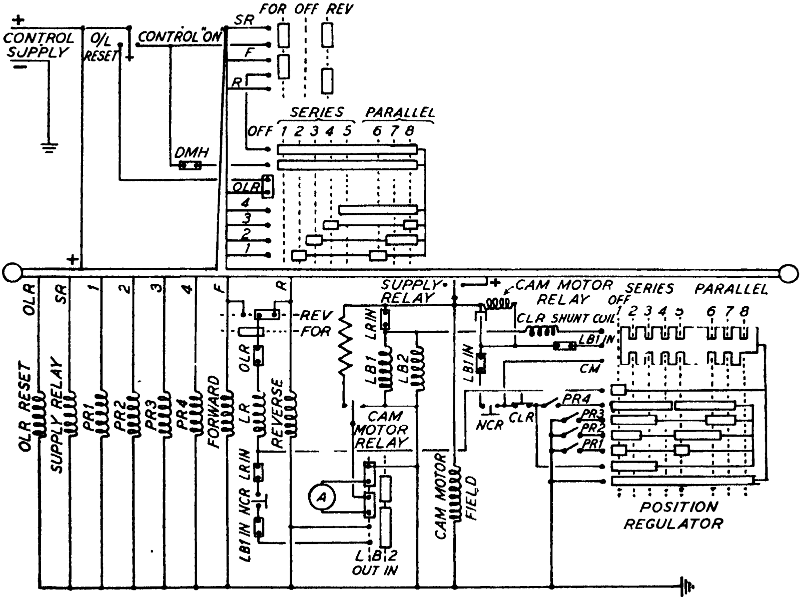


FIG. 88b.—ALL-ELECTRIC CAMSHAFT CONTROL CIRCUITS

equipment is arranged for multiple-unit working, notching up being controlled either by hand or automatically. The auxiliary contacts on the current limit relay are arranged to break the cam-motor relay circuit and so arrest the progress of the camshaft. In order to prevent this happening between notches, the current limit relay has a shunt coil which is energised when the camshaft is between notches to prevent the relay from picking up until the notch is reached.

Referring to the diagram; on closing the control switch and moving the reverse cylinder to a running position, the supply relay is closed by the energising of wire *SR*. When the controller handle is moved to notch one, either wire *F* or wire *R* is energised according to the position of the reverse cylinder. This throws the reverser to its correct position, and then by means of the reverser auxiliary contacts, which check the position of the reverser, *LR* contactor will close providing that the overload relay is set and the camshaft is in the "off" position. When *LR* has closed, a supply is connected from the supply relay to the line breaker operating coils by means of "*LR* in" interlock, and

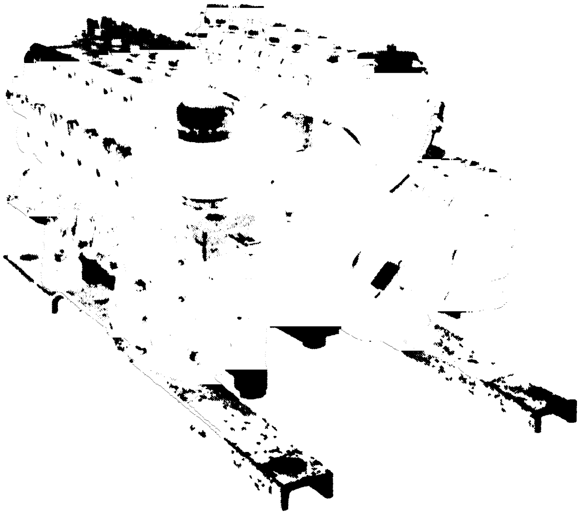
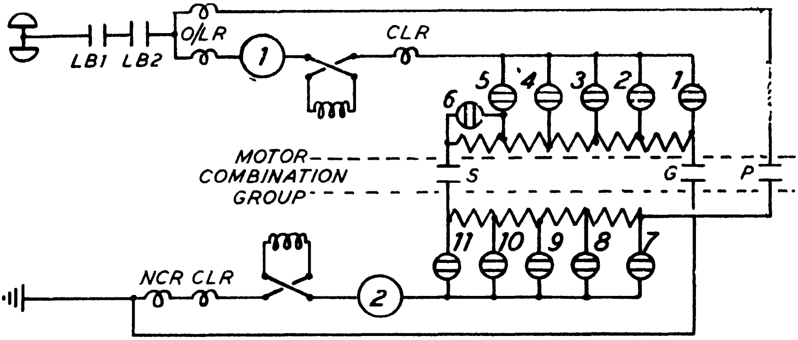


FIG. 89.—LIGHTWEIGHT E.P. CAMSHAFT CONTROLLER

(*B.T.H.*



STEP	PC POSN.	LB1	LB2	P	S	G	1	2	3	4	5	6	7	8	9	10	11
OFF	1				●		●						●				
1	1	●	●		●		●						●				
2	2	●	●		●		●					●	●				
3	3	●	●		●			●				●	●	●			
4	4	●	●		●			●				●		●	●		
5	5	●	●		●			●	●			●			●		
6	6	●	●		●				●	●		●			●		
7	7	●	●		●					●		●			●	●	
8	8	●	●		●					●		●				●	●
9	9	●	●		●					●	●	●					●
10	10	●	●		●						●	●					●
T	10	●	●	●	●	●					●	●					●
10	10	●	●	●		●					●	●					●
11	9	●	●	●		●				●	●	●					●
12	8	●	●	●		●				●		●				●	●
13	7	●	●	●		●				●		●			●	●	
14	6	●	●	●		●			●	●		●			●		
15	5	●	●	●		●		●	●			●			●		
16	4	●	●	●		●		●				●		●	●		
17	3	●	●	●		●		●				●	●	●			
18	2	●	●	●		●	●					●	●				
19	1	●	●	●		●	●						●				

FIG. 90.—MULTI-NOTCH E.P. CAMSHAFT POWER CIRCUIT AND CHART

*LB*1, *LB*2 close. As cam-contactors 8 and 10 are closed at the "off" position of the camshaft, the power circuit is completed with all the four motors and their starting resistances connected in series. Current is now flowing in this circuit so that the no-current relay *NCR* will be closed, and as *LB*1, *LB*2 are closed, *LR* contactor is retained through the *LB*1, *LB*2 and *NCR* "in" interlocks.

The master controller is then moved to notch 2, and consequently closes *PR*1 one of the position relays, which in turn closes the cam-motor relay through the segments in the position regulator. This applies voltage through the "buffer" resistance and *LB*2 auxiliary contacts to the camshaft motor armature and the camshaft moves forward. The circuit through *PR*1 is broken on leaving notch 1, but the cam-motor relay is retained by the notched segment which connects terminal *CM* direct to earth until notch 2 is reached, at which position the relay drops out and the camshaft stops. Proceeding in the same manner, notches 3, 4 and 5 are obtained by the closing of *PR*2, *PR*3, *PR*4 respectively, notch 6 by closing *PR*1, *PR*4 together, notch 7 by *PR*2, *PR*4 together, and notch 8 by *PR*3 and *PR*4 together.

When the controller is returned to the "off" position, the feed through wires *F* or *R* to contactor *LR* is broken, consequently *LR* opens and is followed by *LB*1 and *LB*2, due to the breaking of their control supply at the "*LR* in" interlock. It will be noted that this sequence first inserts a resistance in the power circuit and then ruptures the line current, the same sequence being produced by the tripping of the overload relay. On *LB*2 opening, its interlocks reverse the camshaft motor armature and, on *LB*1 opening, the cam-motor relay is closed through the "*LB*1 out" interlock and the notched segment, hence the camshaft is returned to the "off" position.

So much for non-automatic operation of the camshaft. Now if the controller is moved to the first notch and immediately up to some higher notch in the sequence, the camshaft is arrested at each notch by the interruption of the cam-motor relay circuit by the current limit relay auxiliary contacts, and is only allowed to

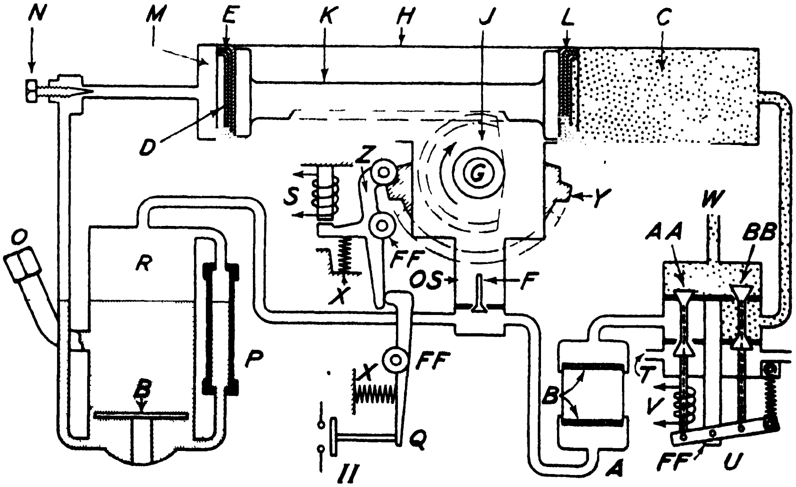
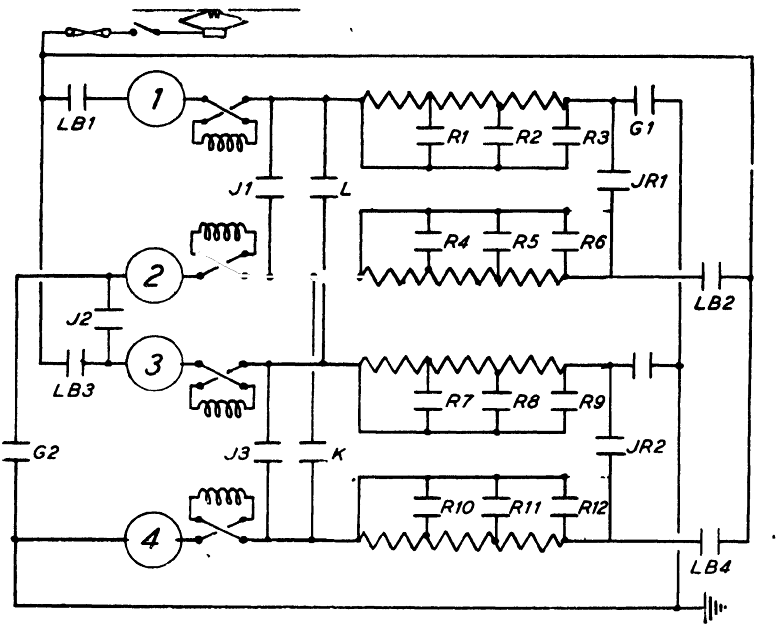


FIG. 91.—RACK AND PINION AIR ENGINE

(*B.T.H.*)



		LB1	LB2	LB3	LB4	J1	J2	J3	G1	G2	G3	JR1	JR2	K	L	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12
SERIES	OFF																										
	1	●					●					●	●			●						●					
	2	●					●					●	●			●			●			●			●		
	3	●					●					●	●			●	●		●			●	●		●		
	4	●					●					●	●			●	●		●	●		●	●		●	●	
	5	●					●					●	●			●	●	●	●	●		●	●	●	●	●	
	6	●					●					●	●			●	●	●	●	●	●	●	●	●	●	●	●
		●				●	●	●				●	●			●	●	●	●	●	●	●	●	●	●	●	●
	7	●				●	●	●				●	●			●						●					
		●					●					●	●			●						●					
		●					●			●		●	●			●						●					
SERIES-PARALLEL	8	●		●						●		●	●			●						●					
	9	●		●						●		●	●	●	●	●			●			●			●		
	10	●		●						●		●	●	●	●	●	●		●			●	●		●		
	11	●		●						●		●	●	●	●	●	●		●	●		●	●		●	●	
	12	●		●						●		●	●	●	●	●	●	●	●	●		●	●	●	●	●	
	13	●		●						●		●	●	●	●		●	●		●	●		●	●		●	●
		●		●		●		●		●		●	●	●	●		●	●		●	●		●	●		●	●
	14	●		●		●		●		●																	
		●	●	●	●	●		●	●	●	●																
PARALLEL	15	●	●	●	●				●	●	●																
	16	●	●	●	●				●	●	●			●	●	●						●					
	17	●	●	●	●				●	●	●			●	●	●			●			●			●		
	18	●	●	●	●				●	●	●			●	●	●	●		●			●	●		●		
	19	●	●	●	●				●	●	●			●	●		●		●	●			●		●	●	
	20	●	●	●	●				●	●	●			●	●		●	●		●			●	●		●	
	21	●	●	●	●				●	●	●			●	●			●		●	●			●		●	●

FIG. 92.—DOUBLE SERIES-PARALLEL CONTROL FOR FOUR MOTORS

proceed after the main circuit current has fallen to the set value of the current limit relay.

ELECTRO-PNEUMATIC CAMSHAFT EQUIPMENT

Modern equipment of this type is tending towards a multi-notch sequence with nine or more steps in each of the series and parallel positions. The camshaft controller illustrated in Fig. 89 is of rather a novel type, in that the camshaft makes almost a complete revolution from the "off" up to the full series position. At this point the motor connections are changed from series to parallel using bridge transition by means of a separate pneumatic switch. The camshaft is then reversed, returns to its initial position and in so doing brings the motors up to the full parallel running position. On reaching this point it is only necessary to open the line breakers, throw the pneumatic switch back to the series connection, and the equipment is ready for starting again. The power circuits and contactor chart are shown in Fig. 90.

The controller itself consist of a number of cam-operated contactors, the camshaft being rotated by a rack and pinion air engine shown diagrammatically in Fig. 91. From this it will be seen that the energising of the magnet valve *U* admits air to the oil reservoir *R* and exhausts the air cylinder *C*, and consequently the piston *K* moves to the left at a speed determined by the adjustable orifice *N* through which the oil must flow. This movement operates the contactors in the sequence required for acceleration in series, the limit of travel representing the full series position. At this point the motor connections are changed from series to parallel on the separate pneumatic switch, and at the same time the magnet valve *U* is de-energised, hence air is admitted to cylinder *C* and exhausted from reservoir *R*, thereby causing the piston to return to its initial position and in so doing operate the contactors in the sequence for parallel acceleration. Notches are definitely located by means of a star wheel mounted on the cam shaft, which engages a pawl operated by a solenoid, so that when energised, the pawl is depressed and locks the camshaft on any notch. Automatic acceleration is carried out by a relay operating on the current limit principle, whose contacts control the energising circuit of the solenoid, so locking the camshaft at each notch until the main current has fallen to a set value, regardless of the fact that air pressure is applied continuously to one cylinder of the air engine.

The line-breakers are electro-pneumatic contactors separate

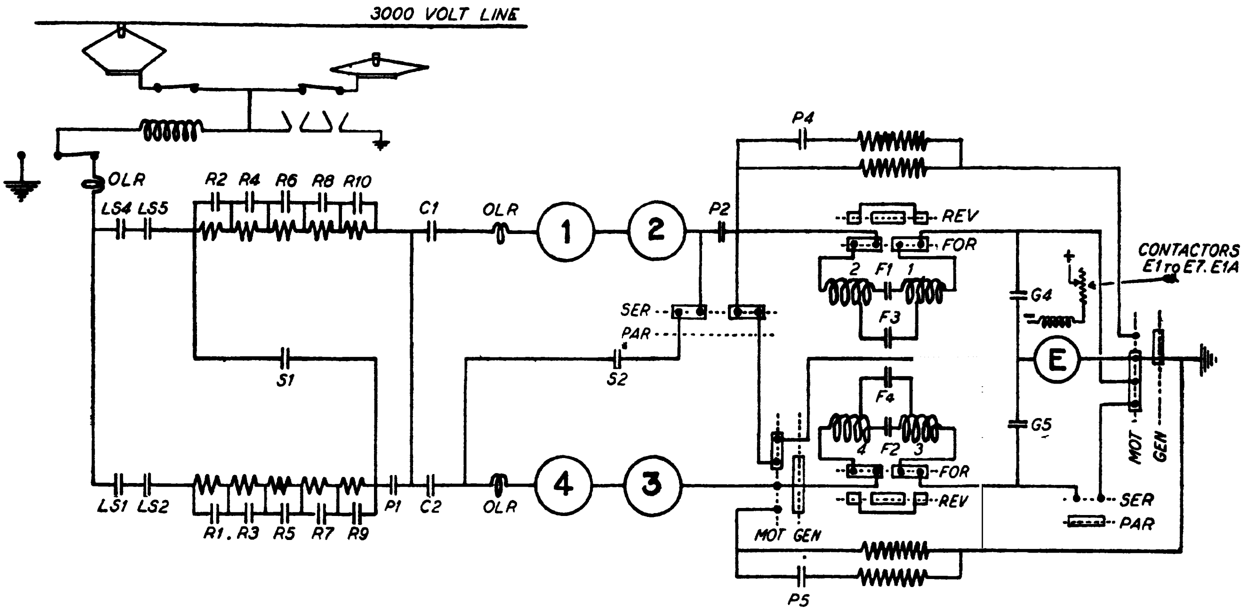


FIG. 93a(1).—SOUTH AFRICAN RAILWAYS LOCOMOTIVE POWER CIRCUITS

(*Metro-Vickers*)

from the camshaft itself, controlled in the usual way. Field shunting for further speed is carried out when required on a separate pneumatic switch, which operates only when the motors are connected in the full parallel running position.

CONTROL GEAR FOR ELECTRIC LOCOMOTIVES

As the load which any particular electric locomotive is required to haul varies considerably in both weight and character, it is not normal practice to make any attempt to equip locomotives with automatic acceleration control. The frequency at which restarts occur is much smaller, and the rates of acceleration much lower than those encountered with motor-coach stock. In order to provide for smooth acceleration, more resistance steps are necessary and where the number of motors is four or more and conditions permit, three combinations of motor connection are used, viz: All in series, two pairs in series-parallel and all in

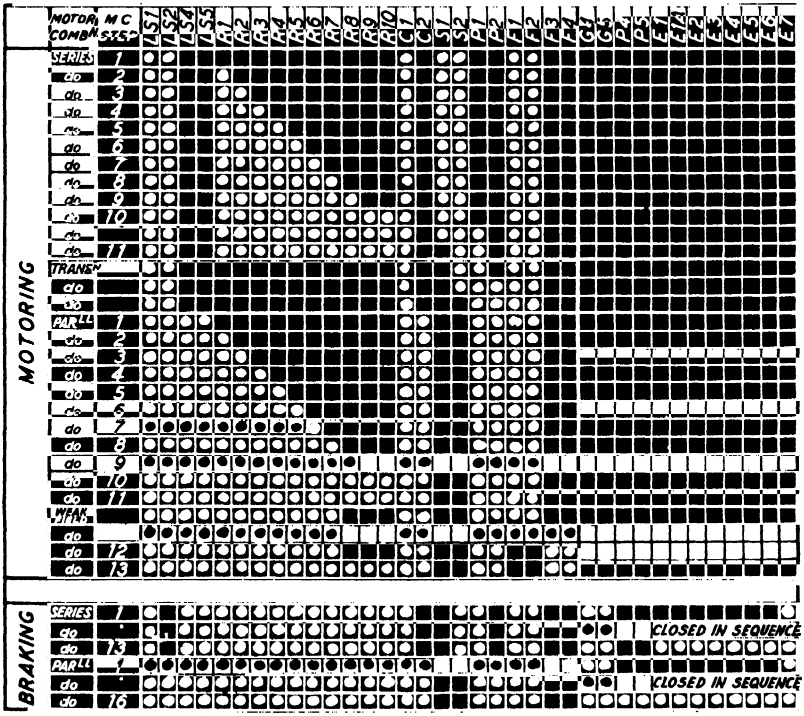


FIG. 93a(2).—SOUTH AFRICAN RAILWAYS LOCOMOTIVE POWER CONTACTOR CHART parallel. By this latter method it is possible to obtain some twenty-five to thirty notches with three economical running speeds at wide intervals of the speed range.

TYPES OF CONTROL

The types of control used are the same as for motor-coach stock, i.e. electromagnetic contactor; electro-pneumatic contactor; all-electric camshaft; electro-pneumatic camshaft. Locomotives are often equipped with control train-line couplings to enable two or more to be operated simultaneously in multiple-unit by one driver.

Two typical schemes are shown in Figs. 92 and 93. The former is a double-series-parallel control scheme (simplified) for a four-motor equipment locomotive supplied at 600 to 1,500 volts, with each traction motor designed to operate on the full line voltage. It will be noted that the motors and their starting resistances are so arranged that shunt transition is employed from series to series-parallel connection, and bridge transition from series-parallel into parallel. Note also the two contactors *K*, *L*, which make equalising connections between corresponding sections of the circuit at certain stages in the sequence, in order to balance the currents flowing in each traction motor and so ensure a fairly even distribution of the load between the four motors. The control scheme is not shown, but is merely an elaboration of that for non-automatic control of two motors (Fig. 82), but with additional interlocking circuits to protect the system from damage if one contactor develops a fault. The power chart provided shows the sequence of closing of the contactors.

Fig. 93a shows the power scheme of a 3,000-volt 1,200-h.p. locomotive equipped with four motors operated in two pairs coupled in permanent series, each motor being designed to run on half the full line voltage. For control purposes the four motors are thus equivalent to two, and are controlled on the series-parallel system.

A fairly wide range of running speeds is provided by having a field tapping on each motor to give two speeds in each of the series and parallel positions. Referring to the diagram; in the series accelerating positions contactors *LS*1, *LS*2, *S*1, *S*2, *C*1 are closed, thirteen steps being provided. Transition is effected using the shunt method by closing contactor *P*2, then opening *S*2 and closing *LS*4, *LS*5, *C*2. To avoid having thirteen series and thirteen parallel steps on the controller, transition is accomplished

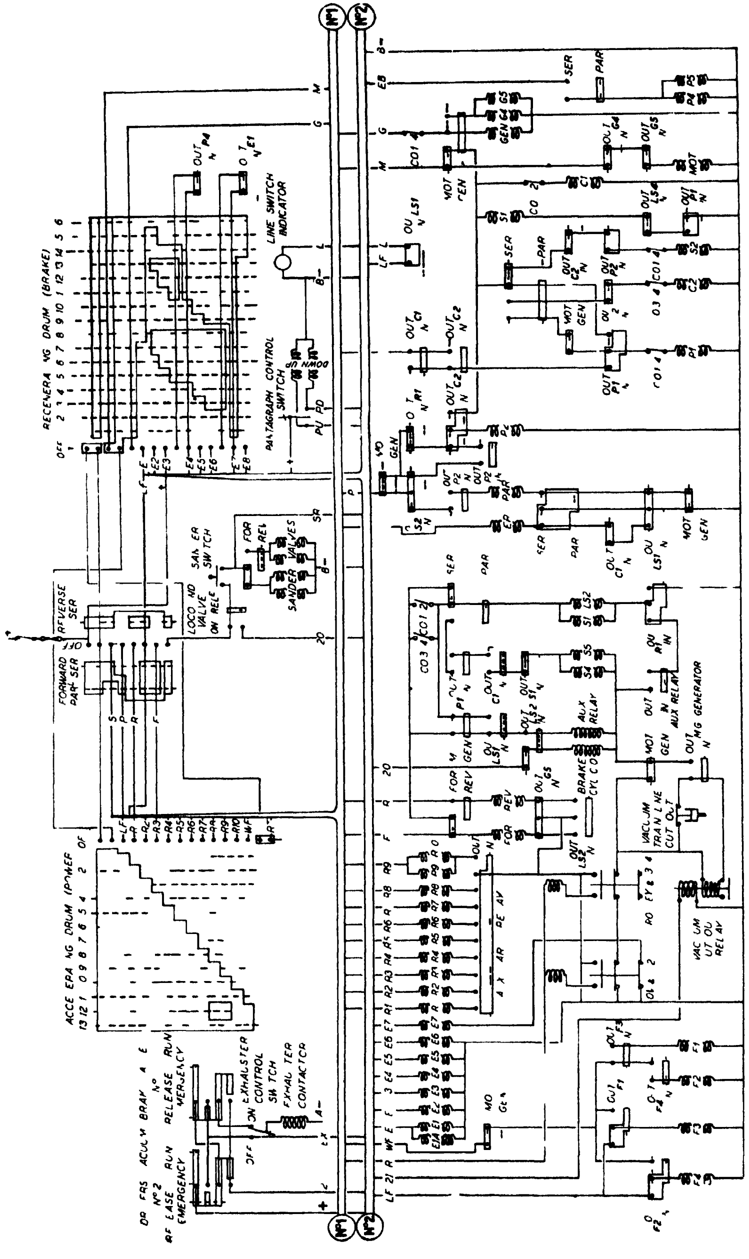


FIG. 93b.—SOUTH AFRICAN RAILWAYS LOCOMOTIVE CONTROL CIRCUITS

(*Metro-Vickers*)

with the aid of a separate drum-type pneumatic change-over switch, so interlocked with the controller that the latter must be returned to notch 1 before transition can be carried out. The reverse handle operates this change-over switch and has extra positions corresponding to the series and parallel combinations, a method frequently adopted on locomotive controllers. Reversal is carried out by a normal electro-pneumatic cylinder-type reverser with segments and fingers.

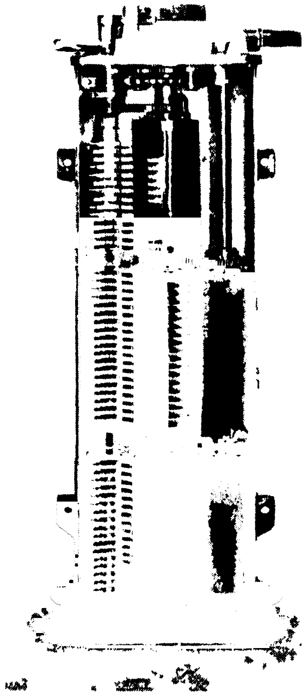


FIG. 94a—LOCOMOTIVE CONTROLLER
(*Metro-Vickers*)

The locomotive is equipped for regenerative braking and carries an exciter "E" for this purpose. Power-brake changeover is effected by a further drum-type electro-pneumatic switch which throws over when the brake handle is moved to the first notch. The control scheme is shown in Fig. 93b.

The master controller is illustrated in Fig. 94a, the three drums being main control, brake control and reverse and motor combination control, interlocking being provided so that only the power or brake may be moved from the "off" position at any particular instant. A similar controller for double-series parallel control is also shown, in which the motor combination drum is separate from that for reversal.

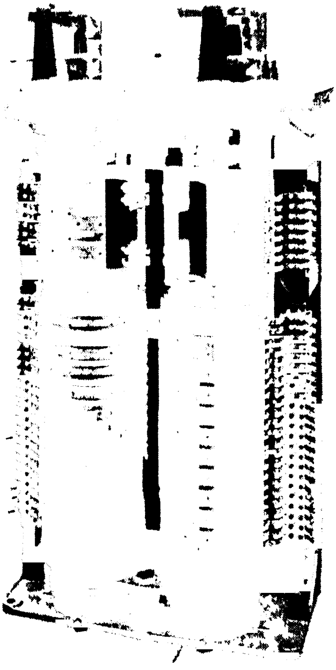


FIG. 94b.—LOCOMOTIVE CONTROLLER
(*Metro-Vickers*)

The complete locomotive is illustrated in Fig. 132. It was designed by the Metropolitan-Vickers Electrical Co. for the South African Government Railways, and over one hundred and sixty of its class have been constructed.

Camshaft control could be utilised with either of the above schemes, in which case many of the sequence interlocks would be unnecessary, and the control circuit would be an elaboration of that shown in Fig. 88, more notches being included.

REGENERATIVE BRAKING

Where the locomotive is used to work heavy trains over steep gradients, it is often desirable to employ regenerative braking when descending these with heavy trains. Besides giving good control of the train and avoiding excessive wear on the brake shoes of the locomotive, the power fed back into the overhead line is considerable, and providing that the sub-station equipment is constructed so as to be receptive to power returned in this manner, the total energy consumption will be substantially reduced. The method employed is to have a low voltage booster set on the locomotive, which is used to separately excite the traction motor fields, the degree of braking being controlled by variation of these field currents under the control of a special braking handle operating a cylinder and normally combined into the master controller. When it is desired to apply the brake, the master controller is returned to the "off" position and the regenerative brake handle moved to its first notch or "brake" position, an action which causes the power-brake change-over switch (Fig. 95) to operate, and so disconnect the motor fields from the power-circuit and connect them to the exciter. The brake is then applied

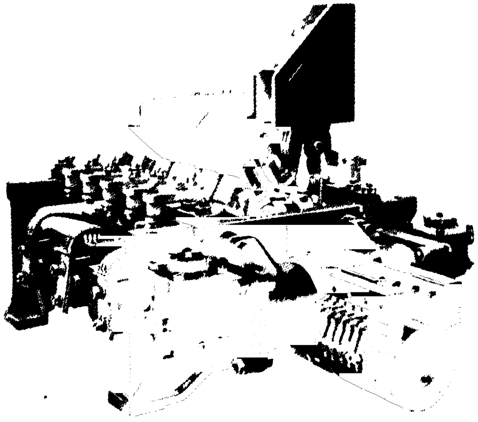


FIG. 95.—CAM-OPERATED CHANGE-OVER SWITCH
(English Electric)

by moving the appropriate control handle to supply field current to the motors, and increasing this until the generated voltage of the motors rises above that in the line and consequently begins to return power thereto. The brake now becomes effective, being proportional to the power returned, and controlled in intensity by variation of the field current.

RHEOSTATIC BRAKING

When the sub-station equipment is not receptive to regenerated power, and a controlled electric braking system is required, rheostatic braking is employed. The system used is somewhat similar to that for regenerative braking, but the generated energy is dissipated in the starting resistances of the locomotive instead of being returned to the line. It is therefore necessary to design these resistances to cope with this energy dissipation over a lengthy period if long descending gradients are likely to be encountered. Furthermore as the braking effort may be adjusted by varying the value of resistance loaded across the armatures, self-excitation may be employed as outlined in chapter 3 for tramway motor control.

Chapter 5

BRAKING AND AUXILIARIES

ALL railway locomotives and motor-coaches require some form of power brake and in consequence are fitted with either exhausters, compressors, or both, in order to have available the necessary braking medium.

EXHAUSTERS

The conditions which must be fulfilled by an exhauster are, (*a*) Its capacity should be sufficient to enable the brakes to be released rapidly, and (*b*) economical continuous operation should be available for maintaining the vacuum when the train is in motion.

These requirements are satisfied by the two-speed exhauster, usually of the rotary type on account of its high efficiency. Fig. 96a shows an exhauster of this type built on the crescent principle. Inside the casing of the machine is an accurately machined and ground cylinder, which is perforated round its circumference by a number of holes, and runs on roller bearings in the fixed end covers of the casing. It is quite free to rotate therein, a suitable clearance being provided by grinding the interior of the case itself.

Inside the rolling drum and running eccentrically to it, is an accurately machined rotor, fitted with sliding radial blades so that when the rotor revolves, centrifugal force causes these blades to press against the inner surface of the rolling drum and this latter, being free to rotate, is carried round by the blades. As air can pass freely through the perforations in the drum, the machine aspires a definite volume of air per revolution due to the blades sweeping the crescent-shaped space. A partially assembled exhauster is shown in Fig. 96b, the various parts described being clearly visible.

This exhauster is always driven by an independent motor frequently of the series type. For rapid releasing of the brakes, this motor's speed is increased by either shunting or tapping its field, or by cutting out of the armature circuit a resistance, which reduces the applied volts to about one-half at normal speed.

Exhauster speed control is from the driver's brake valve, " release " setting giving the high speed, and "running ", " lap " or "on" settings the lower normal one.

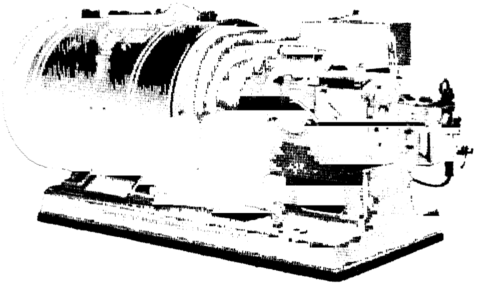


FIG. 96a.—MOTOR EXHAUSTER SET
(*Consolidated Brake*)

COMPRESSORS

Traction equipments which use compressed air for either operation of the control gear, braking, or both, require a compressor capable of delivering air at 100 pounds per sq. in. pressure in sufficient quantities to meet normal demands, allowing for a reasonable amount of leakage which may occur when the equipment is due for overhaul.

A small compressor suitable for trolley-bus and tramway work is shown in Fig. 97a. This compressor is a two-cylinder single-acting machine of unit construction, the armature being carried on an extension of the crankshaft, and the compressor bolted direct to the motor casing. The motor frame and cylinders are provided with ample cooling fins, the cylinders being cast integral with the crank case. The whole unit is supported on insulating bushes from a mounting bracket bolted to the side of the chassis, this being shown in Figs. 120, 121 in the chapter on Rolling Stock.

For railway applications a larger compressor is necessary, and Fig. 97b shows a single-acting horizontal duplex type driven through a double helical reduction gear by a series motor. The view shown is looking from above, the crankcase cover being removed in order to show details of the drive and crankshaft.

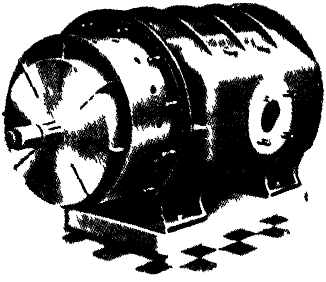


FIG. 96b.—PARTLY ASSEMBLED EXHAUSTER
(*Consolidated Brake*)

In certain cases, such as on diesel-electric locomotives, the compressor is belt-driven from the engine, in which case no driving motor is required.

Provision is made to exhaust any output not required when the pressure is normal in the main reservoir.

Most compressors operate intermittently and are started and stopped by means of a "control governor". This is a pressure-operated switch which open-circuits the driving motor when a pre-determined pressure is reached in the main reservoir, and then restarts it when the pressure has fallen a certain amount. This governor is of the safety valve type, and has two valves set to control a piston which carries the switch contacts. These contacts form the connection between the contact fingers when the governor cuts in and starts the motor. The design of the mechanism provides a pneumatic blowout of such efficiency that no magnetic blowout is necessary on the electrical contacts.

BRAKES

The type of brake employed on tramcars, trolley-buses, or railway equipment is, of course, designed to suit the particular vehicle that it has to control.

It is possible, however, for certain rolling stock to employ more than one system of braking: the tramcar for instance may employ several types of brakes, as enumerated below.

TRAMCAR BRAKING

The modern tramcar may have up to five types of brake fitted, viz.

(*a*) A compressed air brake working on the direct system described later in the chapter.

(*b*) The electric rheostatic brake described in chapter 3, and operated from the controller.

(*c*) The magnetic track brake, which consists of electromagnets suspended close to the running rails and energised by the motor current when rheostatic braking is being used.

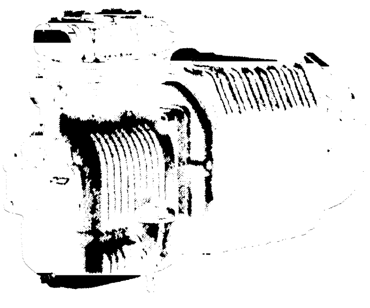


FIG. 97a.—SMALL TRAMWAY COMPRESSOR
(*Westinghouse Brake*)

(*d*) The slipper brake—shoes at each side of the car situated between the driving wheels. These shoes are pressed against the track by rotation of a handwheel mounted beside the controller in the driving position.

(*e*) The wheel brakes—shoes which press on the rims of the wheels, and are mechanically controlled by handles mounted over the slipper brake wheels at each end of the car.

The last two types are equipped with foot-operated ratchets so that the driver, having applied the brake, can lock it in position until he wishes to release it.

The older tramway systems used the wheel and slipper brakes for normal service stops, and the rheostatic brake for emergencies or to control the speed when descending steep gradients. Due however, to competition with motor omnibuses running on the same routes, it was necessary to obtain more efficient braking so that operation at higher scheduled speeds would be possible in safety. This has been done by fitting compressed-air brakes for normal service stops, and magnetic brakes to assist the rheostatic ones for emergency stopping. The old systems are still retained, but are used only in the event of failure of the normal equipment.

TROLLEY-BUS BRAKING

In addition to the regenerative and rheostatic braking arrangements outlined in chapter 3, trolley buses are fitted with direct compressed-air brakes operated from the brake pedal. On depressing this pedal, weak rheostatic braking is first obtained, further depression gives full rheostatic, and pressure beyond this point applies the air brake in addition. Air supply is obtained from a small motor-compressor set mounted on the bus chassis, which keeps the reservoir

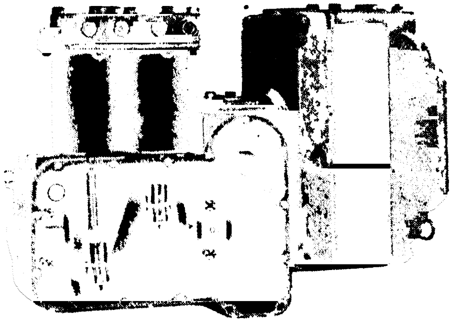


FIG. 97b.—RILAWAY COMPRESSOR
(*Westinghouse Brake*)

charged with a sufficient quantity of air to enable the brakes to remain operative for a time if the trolleys leave the overhead wire. A handbrake lever is also fitted for holding the bus when stationary.

RAILWAY BRAKING

Owing to the high speed of operation and the weight of railway traffic, hand braking arrangements for stopping are entirely inadequate, and such brakes are only used to hold the train when it is at rest. Two types of service brake are used—the compressed-air brake and the vacuum brake.

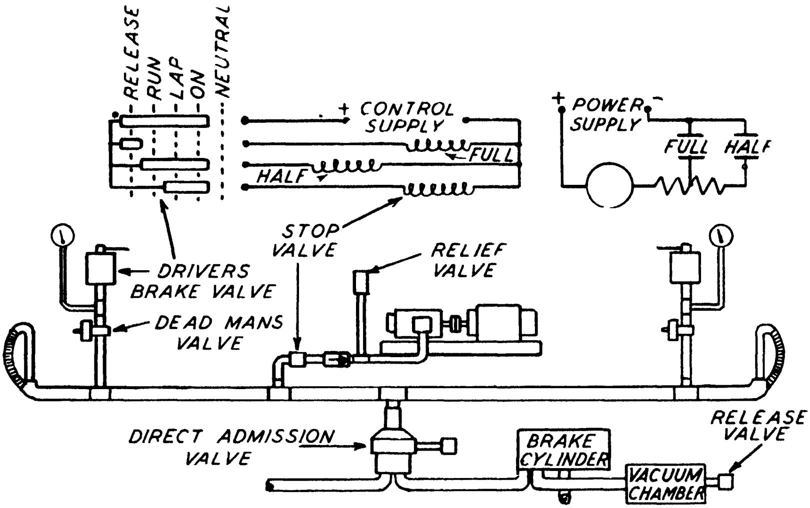


FIG. 98a.—ELECTRICAL CONNECTIONS AND PIPING SCHEME FOR VACUUM BRAKE

THE VACUUM BRAKE

Fig. 98a shows a simplified braking scheme operating on this principle together with the electrical circuits for its control.

The brake cylinder consists of a chamber mounted vertically with a piston inside, this piston being connected to the brake rodding by a piston rod passing through an air-tight gland at the bottom of the cylinder. A vacuum is always maintained on the upper side of the piston, this portion of the cylinder being connected to a vacuum chamber which may be separate, or combined with the brake cylinder in the form of a jacket (Fig. 98b).

To release the brakes, air is drawn from the lower side of the piston until the piston falls to the bottom of the cylinder. When this state has been reached, a higher vacuum exists below the piston than above it, with the result that air is drawn through the non-return valve in the piston, so further evacuating the upper portion of the cylinder and the vacuum chamber. To apply the brake, air is gradually admitted beneath the piston, which moves up the cylinder and hence applies the brakes.

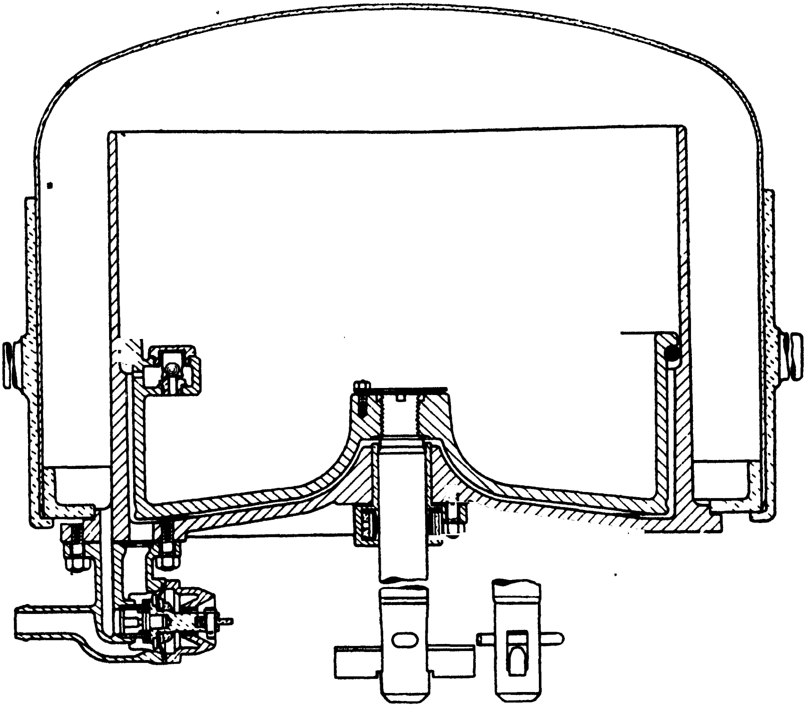


FIG. 98b.—VACUUM BRAKE CYLINDER

Consolidated Brake)

The apparatus is at rest with no vacuum storage before the train is brought into service. To bring the brake into action, the brake valve handle, which is detachable in the "neutral" position, is inserted and moved to "on" or "lap"; this starts the exhauster on half-speed. To release the brakes, the handle is moved to the "release" position, which accelerates the exhauster to full speed and opens the electrical stop valve. This evacuates the whole train system and is continued until about 20 inches of mercury vacuum is obtained. The handle is then returned to the "running" position, thereby reducing the exhauster speed to half its maximum value, amply sufficient to maintain the vacuum whilst the train is in motion.

To apply the brakes the handle is moved to "on", this closes the exhauster stop valve and admits air to the train pipe and brake cylinders, the amount of air admitted being controlled by moving the handle between the "on" and "lap" positions, the latter being a point where air is neither admitted nor exhausted from the system.

BRAKING ON LONG TRAINS

To facilitate braking on long trains a direct admission valve is fitted on each coach. When the vacuum in the train pipe is reduced, these valves admit sufficient air direct from the atmosphere to the brake cylinders, to make the vacuum in these cylinders equal to that in the train pipe. This has the advantage that the driver's brake valve has only to admit air to the train pipe and not to the brake cylinders in addition. Consequently, in an emergency, the brakes may be applied much more rapidly than with the ordinary system.

The release valve to the vacuum chamber is provided so that the vacuum in the upper portion of the brake cylinder may be destroyed, in order to release the brakes when it is necessary for shunting movements.

The dead man's emergency valve admits air to the train pipe in the event of the handle or pedal being released, and is effective in applying the brakes irrespective of the position of the driver's valve. It is usually incorporated inside the master controller.

In multiple-unit stock, the exhauster control, the control supply and the electrical stop valve wires are run through the train line, so that all motor-coaches and exhausters may be controlled from the one driver's brake valve.

THE WESTINGHOUSE AIR BRAKE

The principle of the compressed air brake is that of applying the brakes by means of air pressure on one side of a spring-loaded piston, and releasing them by exhausting the air, so allowing the spring to return the piston to its original position. Two different methods of arrangement are possible, the first being suitable for single independent units such as tramcars, trolley-buses and locomotives not fitted for continuous train braking, and the second

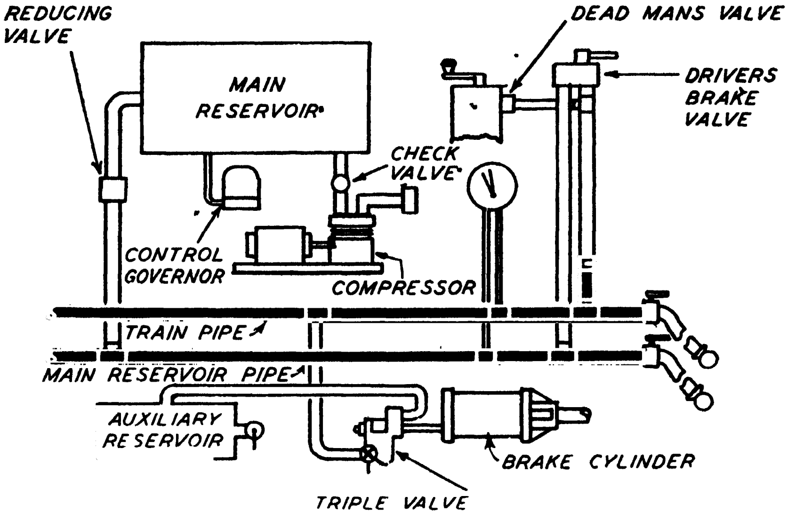


FIG. 99.—THE CONTINUOUS AIR BRAKE

suitable for use on locomotive-hauled or multiple-unit trains where a continuous brake is necessary.

Self-contained units such as trolley vehicles and shunting locomotives use a straight air brake, in which compressed air from the main reservoir is admitted directly to the brake cylinders by means of a driver's brake valve of the self-lapping type, i.e. one in which the strength of the brake application corresponds to the relative position of the handle (or pedal) between the brake "on" and "release" settings. Trolley vehicles have a separate brake cylinder for each wheel in order to equalise the braking torques, but locomotives use only one or two cylinders, the various brake shoes being connected together by rodding.

Fig. 99 shows a simplified scheme for a continuous brake on a complete train, using "triple-valves" to obtain rapid operation of all the brakes on the train. The equipment shown is for a motor-coach, a driving trailer is the same except that no compressor and main reservoir are fitted, while a plain trailer also has no brake valve, gauge or controller. The system operates as follows.

The main reservoir is maintained at a certain pressure by the compressor which runs intermittently under governor control. To release the brakes, the driver moves his brake valve to the "release" position, and so connects the main reservoir pipe to the train pipe. This charges the whole system, including the auxiliary reservoirs, to a pressure of approximately 70 lbs. per sq. in., and this is maintained whilst the train is running under power or coasting. To apply the brakes, the driver moves his handle to the "on" position for a period sufficient to lower the train pipe pressure an amount varying from 5 to 10 lb. per sq. in., and having done this, he returns the handle to the "lap" position. When the handle is in the "on" position, air is released from the train pipe causing a difference in pressure to be set up between this pipe and the auxiliary reservoir at the "triple valve". This pressure difference causes the pistons of the triple valve to operate, and a certain quantity of air is allowed to pass from the auxiliary reservoir to the brake cylinder. When the cylinder pressure has risen an amount proportional to the drop in train pipe pressure, the air supply is cut off. Further decreases in train pipe pressure result in increases in the brake power exerted. This system is known as the "direct application continuous brake".

When a multiple-unit train-set is in operation all driver's brake valves not in use must be isolated by closing the cock *A*, this ensuring that only the cab where the driver is actually situated has an effective brake valve. Should the driver release the dead man's handle, air is allowed to escape from the train pipe, so causing the brake to be applied independent of the position of the driver's brake valve.

ELECTRO-PNEUMATIC BRAKE

A recent development in braking is the Westinghouse electro-pneumatic brake, which is fitted in addition to the normal direct application continuous air brake. This uses a brake valve situated on each coach, electrically controlled from the driver's brake valve through the control train-line, applications or reductions in brake pressure being made by energising the appropriate operating coils on the electro-pneumatic brake valve. The equipment is self-lapping, in that the pressure exerted corresponds to the relative position of the driver's valve handle between the "release" and "on" positions, and hence minute increases and reductions of the braking force may be made. The normal direct application brake is only used in the event of the failure of the electro-pneumatic system.

COMBINED SCHEMES

In cases where a locomotive fitted with compressed air braking is required to operate in conjunction with vacuum braked rolling

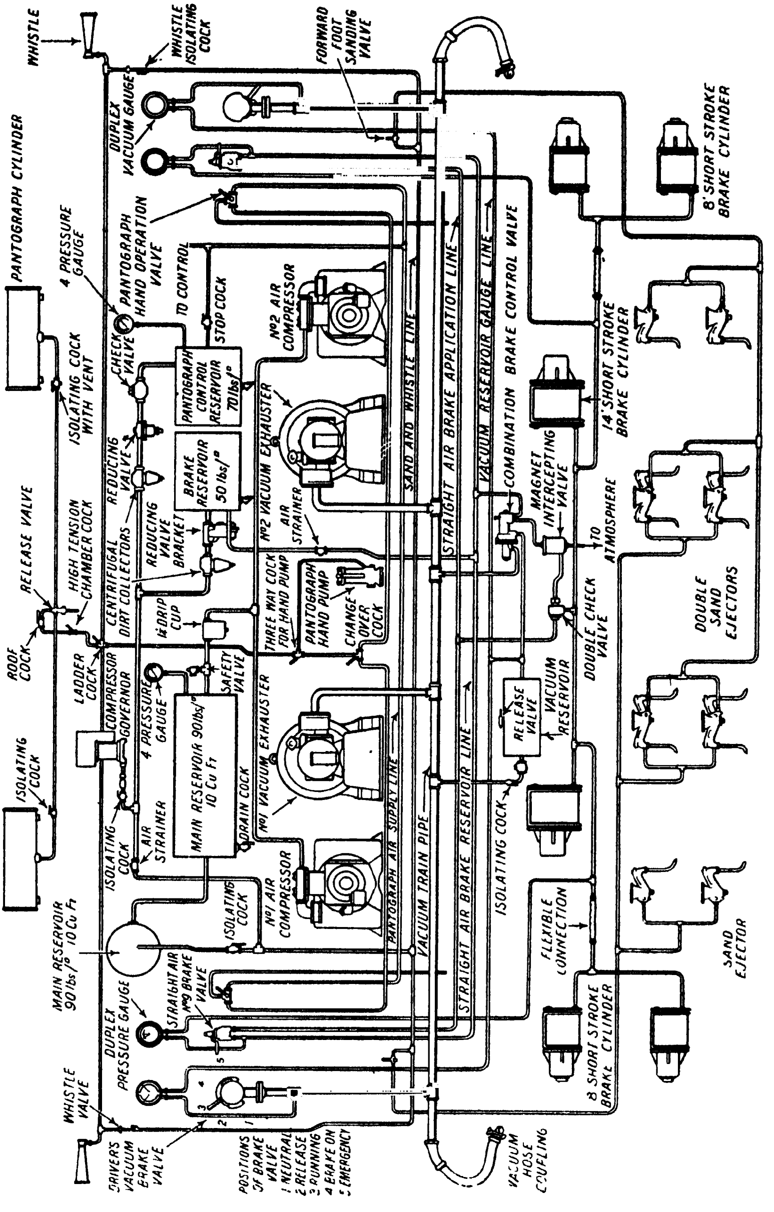


FIG. 100.—COMBINED BRAKE SCHEME FOR ELECTRIC LOCOMOTIVE

(Consolidated Brake)

stock, a dual system is employed. Both compressors and exhausters are mounted on the locomotive, the latter only operating when required. In most cases one driver's brake valve is used to control the locomotive's brakes on the straight air brake principle. In the supply piping to the brake cylinders is fitted a proportional valve, which makes a corresponding vacuum brake application on the train for each normal application on the locomotive.

BLOWERS

The use of forced ventilation for the cooling of main traction motors has already been mentioned in chapter 2. The blower fan may be driven by a separate motor, coupled direct to the engine as in diesel-electric locomotives, or built-in unit with some continuously running auxiliary plant such as a motor-generator set. This ventilation method is confined to locomotive use only, in cases where slow speed or heavily rated motors are employed.

The most convenient system is to arrange for one or two blowers with a total air capacity sufficient for the whole locomotive, the air supply being split up and directed to the motors independently by means of ducting. This ducting of course, is carefully designed with a view to ensuring that the air volume is distributed uniformly between the motors.

On a typical blower, the fan housing is of pressed steel and the exhaust port is shaped to facilitate flange jointing to rectangular steel ducting. The fan rotor is usually of the centrifugal type, with the blades fixed between the main driving body and an outer steel ring. An average figure of power absorbed by this type of blower is 2 h.p. per 1,000 cu.ft. per minute of air delivered at a normal pressure.

BLOWER DRIVING MOTORS

The blower driving motors are generally run direct from the main high-tension supply, even with voltages as high as 3000 volts D.C. Such a motor as the latter of course is relatively large in size for its output, heavily insulated windings and a high number of armature slots being necessary to accommodate the conductors together with a correspondingly large commutator. A series-wound motor is used, as it is permanently loaded on the blower, and allows the introduction of direct-on starting with a series-connected buffer-resistance, in order to limit the peak starting current and also damp down the peaks due to supply interruptions, such as encountered when passing over section-isolators with overhead wires, or at junctions and crossings on third-rail systems.

LOW-TENSION GENERATORS AND MOTOR-GENERATOR SETS

The use of low-tension power for auxiliary and main remote control circuits is general on high-tension electric traction systems, in that lighter insulation of control-gear holds a large saving in space, and also the question of arc suppression at master controller contacts, interlocks etc., is much more easily dealt with. Voltages in use vary from 70 to 150 volts.

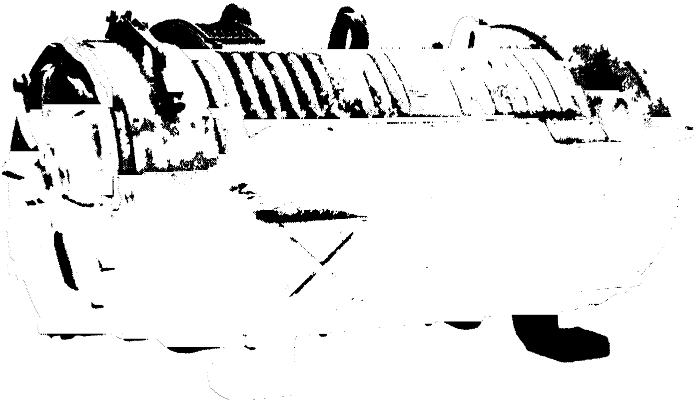


FIG. 101.—MOTOR-GENERATOR SET

(English Electric)

Standard practice is to use a battery in parallel with the L.T. generator as a stabiliser and a reserve of power. Many types of L.T. generators are in use, including direct-driven, motor-driven, and unit constructed motor-generator sets. The former types are in use on existing steam hauled railway rolling stock, where the generator is belt-driven from one of the bogie axles, each coach having an independent unit. On modern diesel-electric equipment, the L.T. generator is either driven directly on the main generator shaft, the two generators forming a unit, or belt-driven from the shaft.

Unit constructed motor-generator sets are in common use on electric locomotives and motor-coach stock, in the latter case the M.G. set being underslung from the coach frame. Fig. 101 shows such an M.G. set suitable for underframe mounting, a special feature of the machine being that it is totally enclosed but externally ventilated by a fan fitted on the shaft at the generator end and enclosed by a metal cowl. The air is drawn in at the fan end, passes along axial frame ducts, and is exhausted through openings at the motor end of the frame. The motor operates from the H.T. supply continuously, and is arranged for direct-on starting with a permanently connected series buffer resistance, which absorbs approximately 5 per cent of the applied voltage at the continuous rated load. Main field flux is provided by a shunt winding, but in order to facilitate direct-on starting a light series compounding winding is also provided. The L.T. end has a continuous rated output of 5 K.W. at 75 volts, and main excitation is by self-excited shunt field coils and series compounding turns carrying the motor line current. This ensures that the generator builds up immediately on starting, and in the correct polarity. The set is used in conjunction with an automatic generator shunt field regulator in order to maintain a constant output voltage at all loads.

This description covers the essential characteristics of L.T. supply sets for control operation, battery charging and the various auxiliary duties in use on railway equipments. The mechanical arrangements differ considerably of course, and in the case of locomotive equipment for instance where the motor-generator set is usually mounted in the locomotive, straightforward self-ventilation only is necessary.

LIGHTING

With the introduction in recent years of all-metal coach work on trolley-buses, the provision of low tension lighting is absolutely essential, where the risk of a fault giving rise to the body becoming live at the high-tension line volts while insulated from ground on pneumatic tyres, is a potential danger to passengers. The earlier practice was that of using a small motor-generator set of either separate machines or unit construction, the motor being of the series type, continuously rated, and suitable for direct-on starting from the main overhead supply.

The usual voltages used for trolley-bus lighting are from 24 to 30 volts, a generator of 1,000 watts output, working in parallel

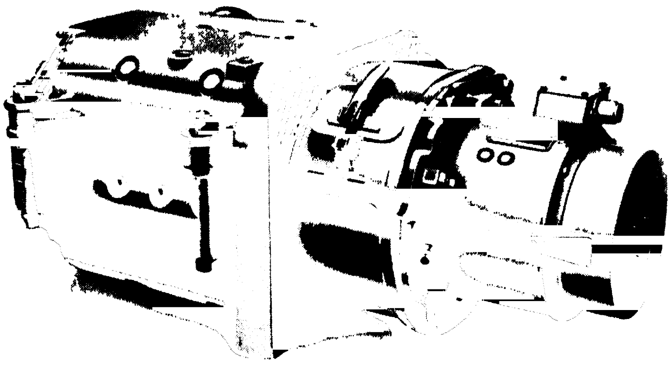


FIG. 102.—TROLLEY-BUS MOTOR WITH OVERHUNG GENERATOR (*B.T.H.*)

with a battery through a combined discharge cut-out relay and automatic generator voltage regulator, being quite satisfactory.

With the more recent developments in trolley-bus equipment, a more economical type of lighting generator, both in construction and in running costs has been introduced. This is a 1,000 watt generator mounted on the armature shaft of the main traction motor and overhung from the non-driving end of the motor, Fig. 102.

A special automatic voltage regulator, of the carbon pile type, capable of handling a wide range of shunt field current, maintains constant voltage output at the generator terminals from maximum motor speed to a minimum corresponding to 4 m.p.h. at which the battery cut-out relay operates.

BATTERIES

Two types of battery are used for traction purposes; the lead-acid battery, and the nickel-cadmium accumulator.

THE LEAD-ACID BATTERY

The lead-acid battery has been used to a large extent on trolley-buses and in railway work, and has given very satisfactory service. Certain limitations in size are necessary, e.g. a trolley-bus battery must not weigh more than 3½ cwts., even if the vehicle is fitted for battery manœuvring. This moderate-sized battery however, has been so designed and improved, that it can propel a vehicle at a speed of 4 to 5 m.p.h. for about 30 minutes.

THE NICKEL-CADMIUM ACCUMULATOR

The nickel-cadmium accumulator, while more expensive in initial outlay, has several important advantages:—
(1) Its life is much longer. (2) The cell is capable of standing indefinitely on open circuit without any deterioration whatever. (3) Heavy currents do not damage the cell. (4) It has great mechanical strength due to all-steel construction. (5) High rates of charging or overcharge are withstood without difficulty providing the solution covers the plates at all times and the temperature is not allowed to exceed 120° F.

A typical battery cell is shown in Fig. 103. It will be seen that the plates are built up with pockets of finely perforated steel totally enclosing the active material. This is nickel hydroxide in the positive plate and a mixture of cadmium and iron in the negative plate. The electrolyte is a solution of potassium hydrate which has no action on the plates. The whole is enclosed in a plated steel container making one cell, the cells being mounted in hardwood insulating crates for protection and ease of handling.

The average voltage per cell of Nife Nickel-Cadmium Alkaline accumulators is 1·2 volts when discharged at normal rate and therefore it is necessary to use more cells per battery for a given voltage than is the case with accumulators of the lead-acid type.

COACH HEATING

Heating of electrically propelled trains may be divided into two categories.

(*a*) Electric trains composed of motor coaches and trailers.
(*b*) Ordinary trains hauled by an electric locomotive which may be replaced by steam traction at some stage of the journey.

Electric multiple-unit stock is always heated by means of heaters of the element type as used in electric radiators. With compartment stock a maximum of 600 watts is required to keep a comfortable atmosphere, hence the heaters are so designed and arranged that either 300 watts or 600 watts may be supplied in each compartment. On trains operating on 600 volts, the heaters are arranged in two parallel circuits, each circuit consisting of say

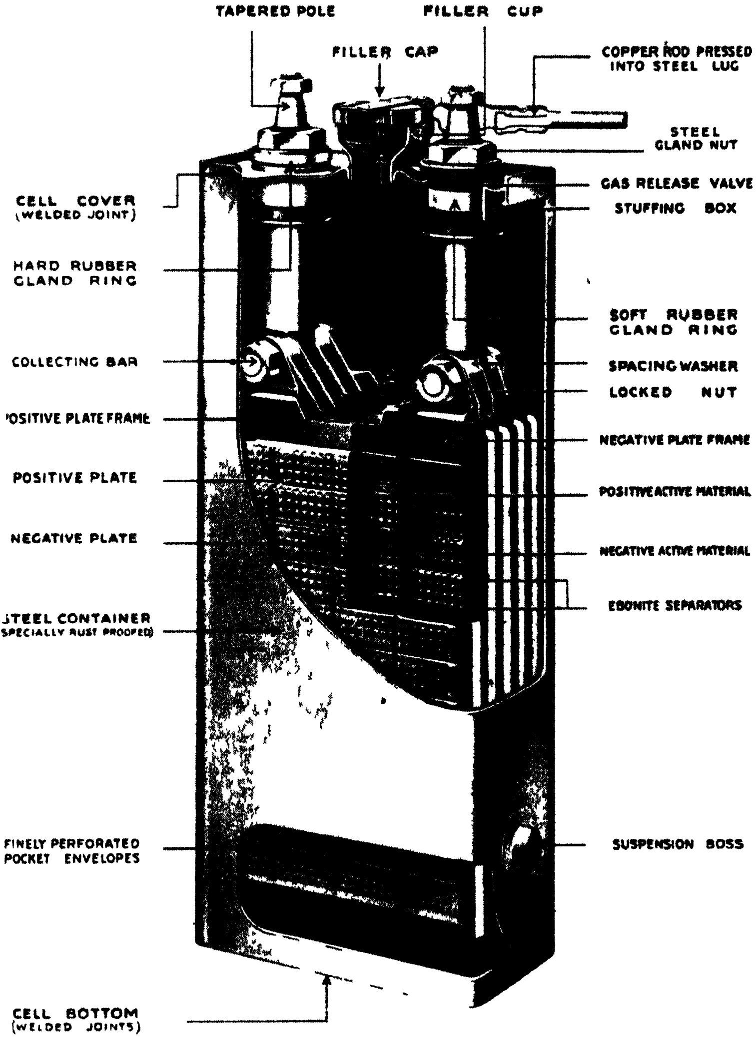


FIG. 103.—NIFE NICKEL-CADMIUM ALKALINE ACCUMULATOR IN SECTION

(*Nife Batteries Ltd.*)

ten heaters in series arranged one in each compartment. On high voltage stock the same system is employed, all the heaters being specially insulated to provide adequate protection against danger from faults.

The heater used in any particular stock is standardised, and where the number of compartments is insufficient to use all the heaters in the series circuit, those in excess are mounted either in the guard's compartment or on the underframe. Two types of coach heater are in normal use. Type (*a*) consists of a stretched spiral element, wound in a spiral on a porcelain former, the whole being mounted in a perforated metal case, no glow being visible due to the working temperature of the element being below red heat. Type (*b*) consists of a tubular element mounted concentrically in a steel protecting tube. In both cases the insulation provided must be sufficient to withstand the total voltage on the circuit.

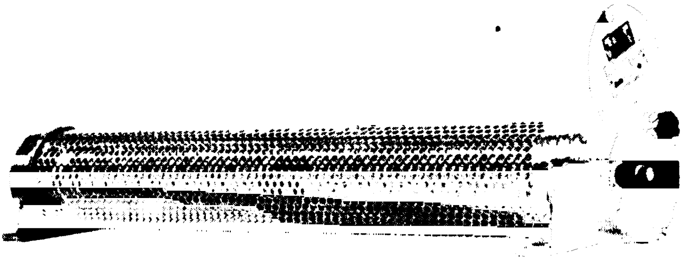


FIG. 104.—400-WATT COACH HEATER

(*English Electric*)

With an electric locomotive which is used to haul ordinary stock, it usually happens that the coaching stock is fitted for steam heating. As it is undesirable to convert the whole of the coaching stock which may be used with electric haulage to dual heating by steam or electricity, a boiler is carried on the locomotive to provide low pressure steam for heating. Two types of boiler are normally employed, oil fired or electrically heated. In both cases pressure control may be arranged, so that when the steam reaches the required pressure, the fuel or electricity being supplied to the boiler is either cut off entirely or reduced to a very small amount sufficient only to maintain the pressure with no load on the boiler. Safety valves are fitted to the boiler and set to operate when the pressure slightly exceeds that at which the heating is reduced. An electrically-heated locomotive boiler is shown in Fig. 105, the loading being 300 K.W. at 600 V.

COACH LIGHTING

On electric locomotive hauled coaching stock the existing lighting from small generators belt-driven from the coach bogies is almost always retained. With electric trains working on the multiple-unit system however, coach lighting is supplied from the low-tension generator or from the high-tension supply, if this is of the order of 600 volts, in which case several lamps are connected in series in order to avoid excessively high-voltage lamps. The control of lighting is usually by means of a trip and set relay or contactor, which is operated by the guard or driver. To switch on the lights, the setting coil is momentarily energised from a push-button, the relay or contactor closes and remains closed until tripped by energising the trip coil from a further push-button.

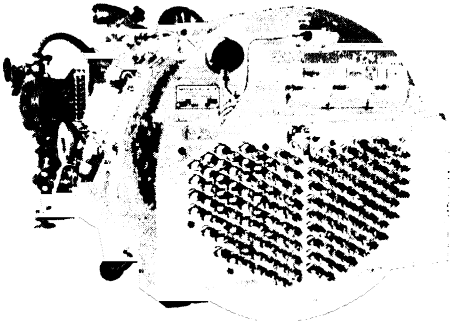


FIG. 105.—ELECTRICALLY HEATED LOCOMOTIVE BOILER
(*Bastian and Allen*)

Such a relay or contactor is mounted in each coach, and controlled through the lighting train-line.

Chapter 6

POWER SUPPLY AND COLLECTION

THE main power source for any direct current traction scheme is usually one large central power station owned by the operating company. Power is generated as alternating current at a high voltage, and transmitted to sub-stations spaced at intervals throughout the length of the system. The only exceptions to this rule are the local tramway and trolley-bus companies, who obtain their power from the municipal power station, convert it immediately to 600–650 volts direct current and feed the various sections of their system through feeders and isolating switches.

CHOICE OF VOLTAGE

The choice of the transmitting voltage from power station to sub-stations is governed by several factors, some of which are outlined in the following.

(*a*) The largest distance over which the power has to be transmitted; on lengthy systems a higher voltage is more suitable as less losses are incurred.

(*b*) The total amount of traffic being operated over the whole system.

(*c*) The initial cost, which is greater for higher voltage apparatus due to the heavier insulation involved.

(*d*) Existing power supply networks, where these are likely to be used.

SUB-STATIONS

On receipt at the sub-stations the high voltage A.C. is converted to direct current at the operating voltage of the system by either transformers and rectifiers, or by rotary convertors. The modern tendency is to use mercury-arc rectifiers, and a brief description of the plant at a typical sub-station using such rectifiers now follows.

The incoming three-phase high voltage feeder terminates in a hand-operated oil circuit breaker. Each rectifier transformer is fed from this through a motor-operated oil circuit breaker, controlled from the sub-station switchboard. These rectifier transformers drop the A.C. voltage to that which, after rectification, will give the correct line operating voltage, the output to the rectifiers being six-phase. The rectifiers themselves are of the steel tank water-cooled continuously pumped type, the whole equipment being insulator mounted to minimise losses and electrolytic action (Fig. 106). The number of rectifiers in use will depend on the number of sections of track fed, and the load on the sub-

FIG. 106.—RECTIFIER

(Metro-Vickers)

station. On its direct current side each rectifier is protected by a reverse current and a normal current overload-tripping high-speed circuit breaker. In Fig. 107, these are shown mounted on a raised platform below which are the D.C. bus-bars and switches. The whole equipment is controlled from the sub-station control panel, and this itself is very often arranged for remote control from the central power station, so that apart from maintenance work, the sub-station is unattended.

Dynamic sub-stations, i.e. those containing rotating machinery are still encountered frequently. With these the incoming feeder, after passing through the usual circuit breakers, supplies the driving end of the convertor sets. The D.C. output from these then supplies the various sections of track through the usual circuit breakers and isolating switches. The only advantage possessed by equipment of this type over the rectifier sub-station is that, when regenerative braking is used, it is possible to return power to the main high-tension feeder system. Consequently sub-stations of this type are often installed where the gradients are steep, and locomotives equipped for regenerative braking are to be used; however, due to the recent improvements in the "invertor",

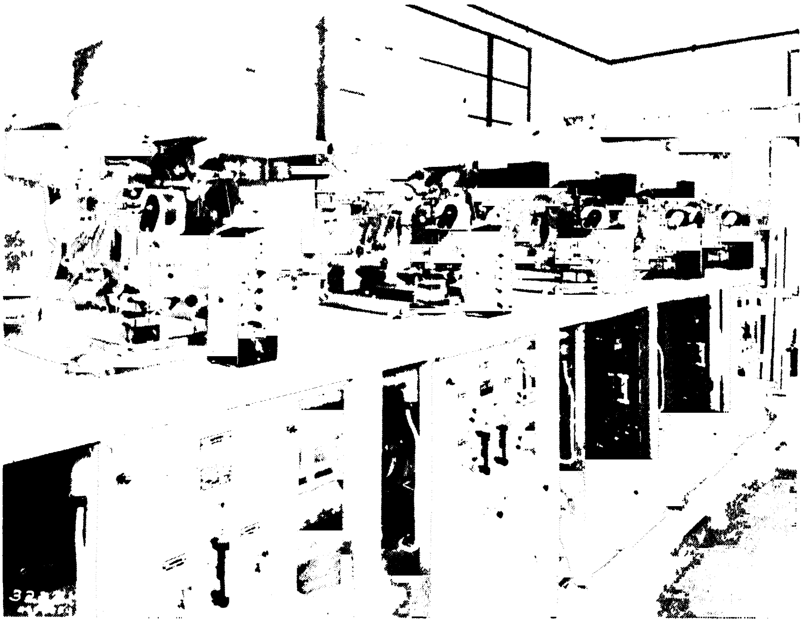


FIG. 107.—HIGH-SPEED CIRCUIT BREAKERS

(B.T.H.)

which is a rectifier working in reverse, it is now becoming possible to have static sub-stations for this type of work.

TRAMWAY SYSTEMS OF COLLECTION

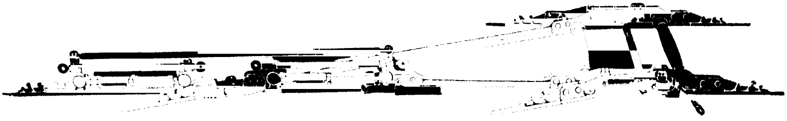
Tramways are usually supplied from an overhead conductor wire suspended above the track at a minimum height of 17 ft., and supported at intervals of not more than 120 ft. The total length of wire on any route must be divided into sections not more than half-a-mile in length, each section being isolated from its neighbours.

The material used for the conductor wire is either hard drawn copper, cadmium copper or bronze. Of these, the modern tendency is to use cadmium copper in view of the fact that, compared with hard drawn copper, its tensile strength is 18 per cent higher for a decrease of only 8 per cent in conductivity. In addition its resistance to wear is much superior, in some instances cadmium copper having a life of three to four times that of hard drawn copper. The cross-section of the wire may be one of two types; round, or round with two grooves spaced 120 degrees apart on the upper half of its circumference.

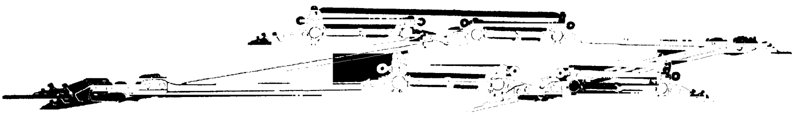
The wire is clamped in "ears", these being suspended from a bolt carried in an insulated mounting known as a "hanger". These hangers are attached to either wires slung between posts erected at each side of the road, or bracket arms carried on posts fixed at one side of the road only. The position of the wire, relative to central above the track, is governed by the type of current collector to be used. With a bow collector, the wire must always be suspended centrally above the track, hence suspension with posts at each side of the road is almost universal. If a swivel head trolley is to be used, satisfactory operation may be obtained with the wire displaced up to 6 ft. from the centre of the track, in which case, providing the roadway is sufficiently narrow, bracket arm suspension from one side of the road may be employed to carry the trolley wires for both directions of running.

At points and crossings in the track, arrangements have to be made in the overhead wires to ensure that the trolley takes the correct route. With points, a mechanical "frog" is used in the facing direction; this is really a miniature point in the wires, operated by a lever mounted above it, which is moved by means of a wire attached to a handle at the roadside.

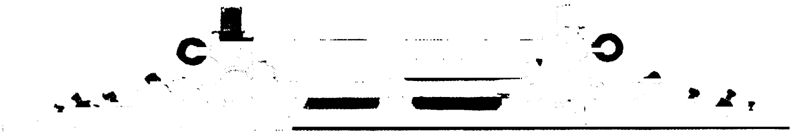
Fig. 108 shows some typical overhead wire fittings.



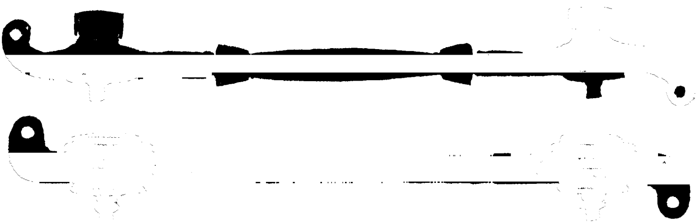
(*a*) Turn-out for Trolley-bus lines



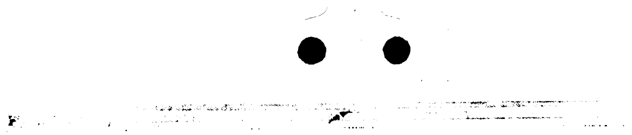
(*b*) Cross-over for Trolley-bus lines



(*c*) Dumb-bell type section insulator



(*d*) Twin hanger for Trolley bus lines



(*e*) Clinch ear for grooved wire

FIG. 108 SOME OVERHEAD WIRE FITTINGS

(*B I Cables*)

TRAMWAY TROLLEYS

Two types of collector are used on tramway systems.

(*a*) This consists of a long boom, swivel-mounted at one end, this end being attached to the roof of the tramcar, and carrying at its outer end a wheel or shoe with which to make contact with the overhead wire. The boom is spring loaded in the upward direction to give a contact pressure on the trolley wire. To allow for the tramcar being operated in either direction, for cornering and for variations in the trolley wire position, the whole boom assembly can be rotated about the point on the roof to which it is attached, and in addition the trolley head, which contains the wheel or shoe, can swivel about a vertical axis. Typical trolley heads, wheel and shoe are shown in Fig. 109. In the shoe type current is actually collected by a carbon brush at the bottom of the groove which slides along the trolley wire.

(*b*) Considerable simplification of wire fittings, together with complete elimination of trouble due to dewirement of the trolley, is obtained by fitting a bow collector. The bow is hinged laterally at its base to allow it to trail in either direction, being thrown over by the driver at each terminus. Actual contact with the wire is made by a swivelling pan carrying a strip of copper which is renewable when worn.

On light industrial locomotives where bow collectors are used, it is impracticable to throw the bow over each time the locomotive is reversed, and hence a reversible bow collector is employed. In this the main frame remains in the one position and the small bow at the top automatically sets itself to trail whatever the direction of motion. (Fig. 110.)

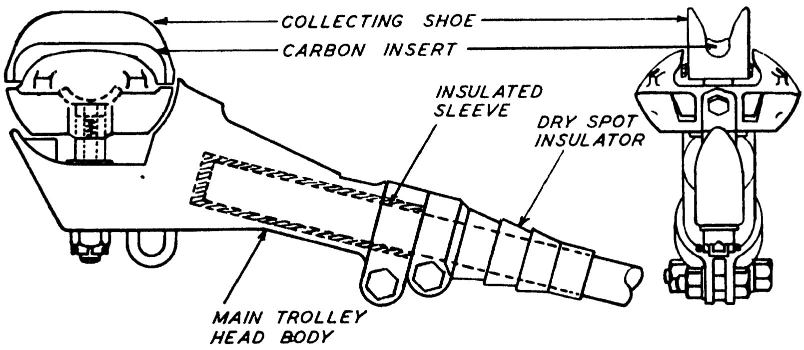
CONDUIT TRAMWAYS

The first conduit tramway was installed in this country in 1884, but the only system of this type now surviving is that operated by the London Passenger Transport Board. Conduit track is of necessity much more complicated in construction than that for overhead wire systems, and this fact doubtless influenced the majority of local authorities in their choice of the latter.

As outlined previously, current is collected by means of a "plough" attached to the underframe of the tramcar, this plough obtaining access to the conductor rails through a slot one inch wide, set centrally between the two track rails. Beneath this slot

FIG. 109a.—TYPICAL TROLLEY HEAD (*English Electric*)

FIG. 109b (below).—SHOE-TYPE TROLLEY HEAD (*English Electric*)



are carried the two conductor rails, consisting of T section high conductivity steel rails, mounted facing each other (e.g. ⊣ ⊢), on insulators hanging from the slot rail supports. One rail is for supply and one for return, the plough having collectors at each side for this purpose. Sections and feeder arrangements are similar to those for an overhead line.

At junctions, etc., it is necessary to have slot points in addition to track points, and these complicate the construction considerably. A typical junction is shown in Fig. 111. Certain parts are made of special manganese steel to withstand the heavy shocks and hard wear received in service.

TROLLEY BUS SUPPLY

Power for a trolley-bus is collected by means of two swivel-headed trolleys mounted side by side on the roof of the vehicle. These run (or slide) along the conductor wires which are suspended above the roadway in a manner similar to that for tramways. However, as wires of both polarities are mounted side by side, insulation between the various points of suspension is necessary. Standard practice is to mount the return wire on the near side of the road, in which case the positive supplies for each direction come together. The wires are carried in ears as previously, these being supported by hangers, thus one insulator is fitted between each line and the supporting wire; a third insulator is fitted between the hangers so that triple insulation is obtained. At points and crossings in the wires where the various routes diverge, provision has to be made for the two wires of opposite polarity to cross each other; this is done by means of insulated crossings. The method of wire suspension and use of "pull-offs", etc. is shown in Fig. 112. Where the roadway is narrow, all four wires may be carried on bracket arms fixed on

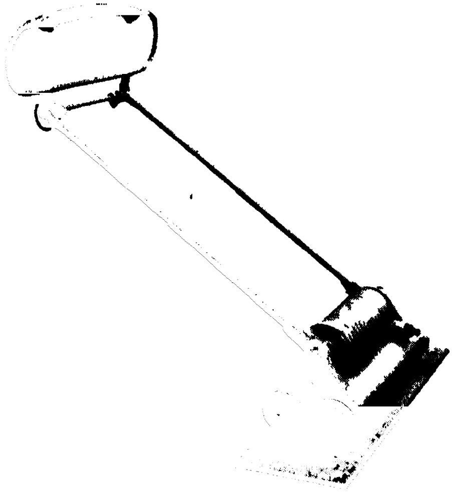


FIG. 110.—REVERSIBLE BOW COLLECTOR
(*English Electric*)

poles at one side of the road, alternatively where the road is very wide, each pair of wires may be independently supported on bracket arms at their respective sides of the road. In all other cases the wire is suspended in the normal manner by cross wires and poles. At certain stopping places, by-pass loops are provided to enable one bus to overtake another travelling in the same direction without their trolleys fouling each other.

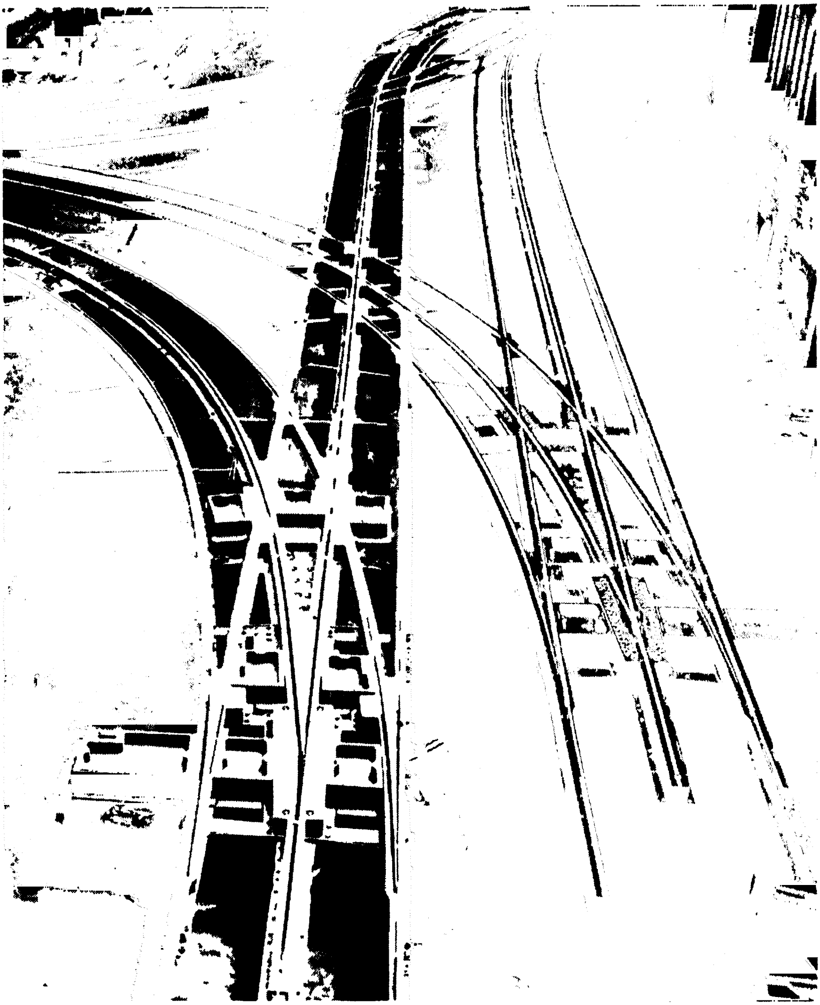


FIG. 111.—CONDUIT TRAMWAY JUNCTION

(*Hadfields*)

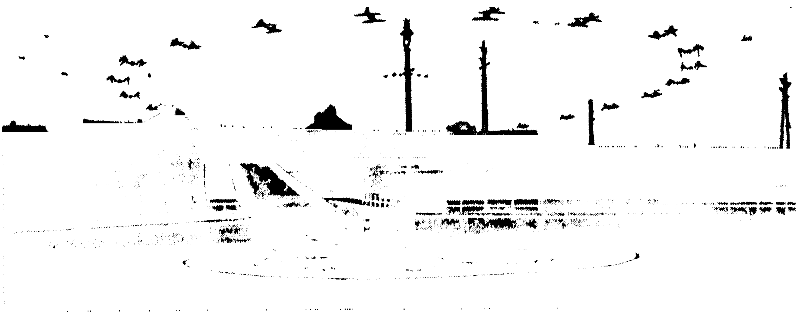


FIG. 112.—TYPICAL OVERHEAD WIRE SUSPENSION
(Sunderland Transport)

The trolleys used on this type of vehicle are similar to those on the tramcar, being swivel-mounted at their bases with rotatable trolley heads. To avoid undue arcing between the trolley wheel and the overhead wire when passing over insulated crossings and section isolators, it is customary to shut off power momentarily. To indicate to the driver when the voltage between the trolleys is interrupted on passing these or by dewirement of one or both trolleys, a dewirement indicator is fitted in the driver's cab, indication being by the extinguishing of a neon lamp or the sounding of a buzzer.

RAILWAY COLLECTION

Current for the operation of railway traffic may be collected in two ways, the actual system employed depending on the operating voltage. When this is of the order of 600 to 1,000 volts a "conductor rail" is commonly used, while for higher voltages, an overhead conductor wire is necessary. The choice of operating voltage is governed by many considerations, amongst which are the type and density of traffic, the operating voltage of other sections of the company's track, the location of sub-stations and main power plant, and the prevailing ground and climatic conditions.

CONDUCTOR RAIL

Collection by conductor rail entails the mounting of an additional (or third) rail on insulators alongside each running track. This third rail is mounted a few inches higher than the running

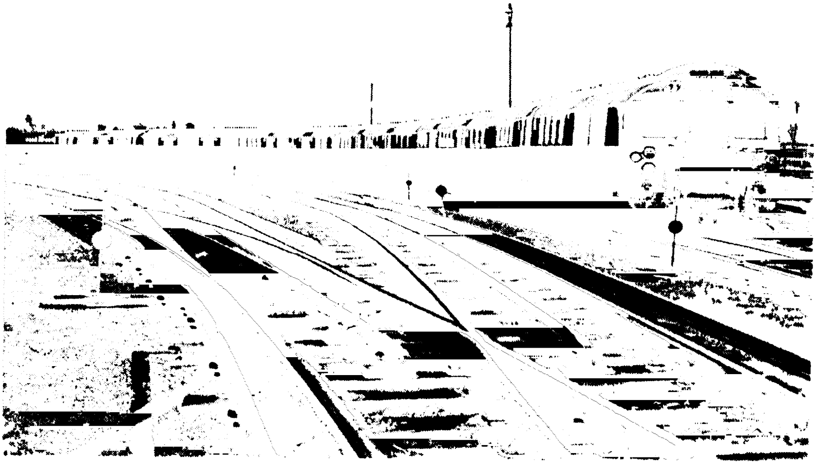


FIG. 113a.—INSULATED RETURN, CONDUCTOR RAIL COLLECTION

(*Metro-Vickers*)

FIG. 113b.—RUNNING RAIL RETURN, CONDUCTOR RAIL COLLECTION

(*English Electric*)

rails in order to allow the collector shoes to be fixed in such a position as to avoid any possibility of their fouling other running tracks at crossings, etc. Steel rails are usually employed for this duty, and are carried on porcelain insulators so designed as to give a large creepage distance to ground. The position of this rail is alternated between the two sides of each running track in order to obtain cooling and equal wear of the collector shoes, and for convenience in maintaining a power supply at junctions, crossings, etc. Current return is made through the wheels and running rails, except in certain cases where an insulated return

FIG. 114.—COLLECTOR SHOE

(*Metro-Vickers*)

rail mounted centrally between the running rails, together with special collector shoes on the train are used. Examples of both these types of track are shown in Fig. 113.

The collector shoes are made of cast iron, and are suspended from wooden beams mounted on certain of the bogies. Each shoe feeds through a fuse into a power train-line, which runs throughout the length of the train, each motor coach taking its supply from this train-line through an isolating switch and fuse.

OVERHEAD COLLECTION

In designing an overhead system of collection many points must be taken into account, e.g. the size of the conductors is

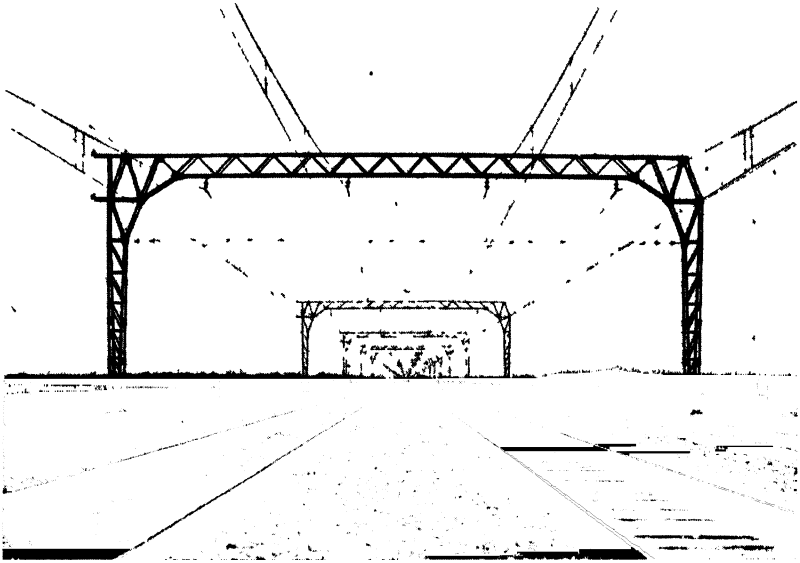


FIG. 115a.—CATENARY SUSPENSION. OVERHEAD EQUIPMENT. FOUR-TRACK CONSTRUCTION

(*B.I. Cables*) (*Indian State Railways*)

governed by the current to be collected, the spacing of the substations and the type of traffic to be dealt with. The spacing of the structures to support the wire is determined by maximum wind and other climatic conditions, whilst the actual type of structure depends on the source of supply of the steel work, and on what provision has to be made for carrying distribution transmission and other wires.

Owing to the higher operating speeds of electric railway trains and the heavier currents involved, the trolley wheel collector and the methods of suspension used in tramway and trolley-bus work are entirely unsuitable. The bow collector has been used to some extent, but most present-day railways employ the pantagraph. As these two types have a much higher inertia than the trolley, they require a level conductor wire carried centrally over each running track. In order to obtain this without excessive wire tension, short spans of approximately ten feet are used, these being obtained by supporting the actual trolley wire by means of droppers hanging from a second wire. This latter wire is suspended with considerable sag between supports spaced between 40 and 80 yds. apart, and is generally known as the "catenary"

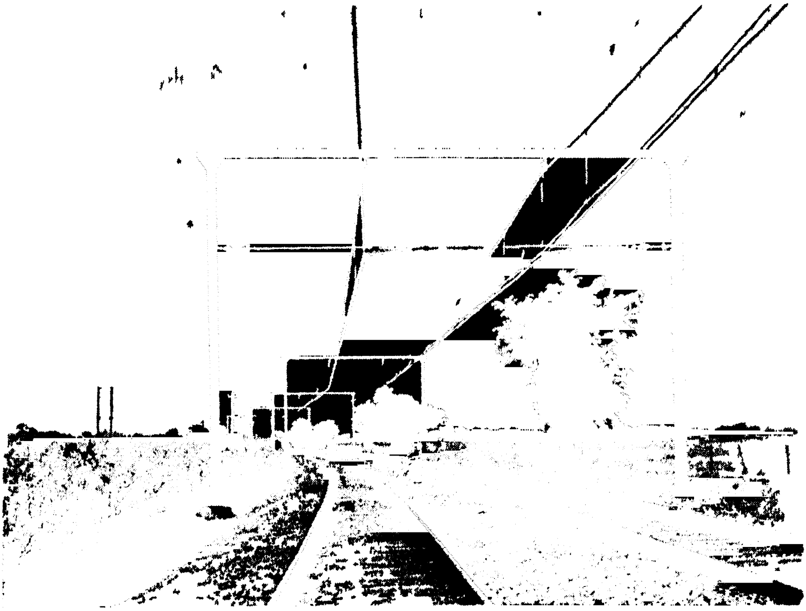


FIG. 115b.—COMPOUND CATENARY SUSPENSION

(*B I Cables*)

It is insulated from the supports but not from the trolley wire itself, and, as it is often made of the same material as the contact wire, (i.e. hard-drawn copper), carries a considerable proportion of the current. The trolley wire is maintained in position by "pull-offs" fixed at each support, these being clearly shown in the illustrations. It is usual to stagger, or "zig-zag" this wire about six inches between the structures, to avoid grooving the collector skates or pans.

Another form of catenary construction is the "compound catenary", consisting of three wires in the same vertical plane. Uppermost comes the catenary wire insulated from the supporting structures; below it the intermediate wire supported by droppers, and then the trolley wire suspended from the intermediate wire by loops, which allow it to move in a direction parallel to the track. Automatic tensioning gear is fitted at the end of each section, and as the trolley wire is free to move, it is maintained at a constant tension under all climatic conditions. Fig. 115 shows typical examples of structures with single and compound catenary suspension on both straight and curved track.

At points and crossings on the track it is unnecessary to have

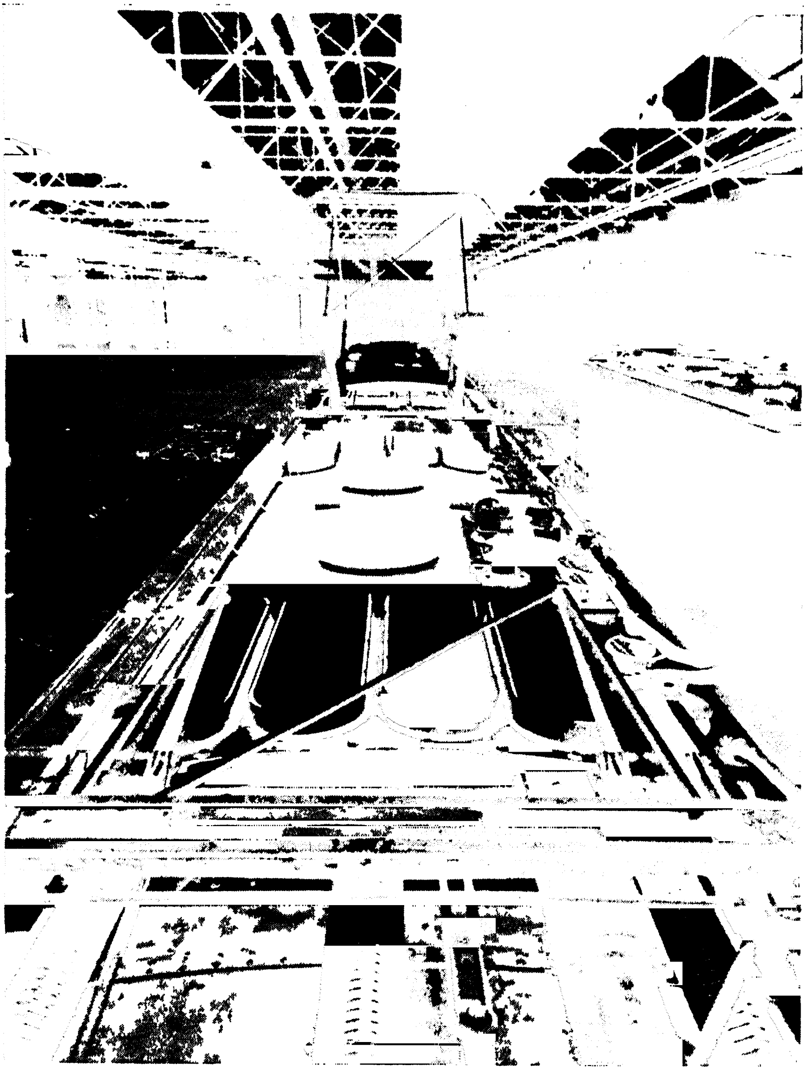


FIG 116—COMPLETE ROOF GEAR OF LOCOMOTIVE

(*Metro-Vickers*)

actual points in the wires. A further set of wires starts at a structure one or two previous to where the junction occurs, runs parallel to and at the same height as the main trolley wire, and then diverges from it as the branch line trolley wire when the junction or crossing is reached.

The same overlapping principle is used at the end of each section in the trolley wire.

PANTAGRAPH

The complete roof gear of a locomotive is shown in Fig. 116. Current is collected by means of the pantagraph, and passed to the locomotive's control equipment through a fuse, a choke coil, and a lightning arrester.

The pantagraph consists of a strong steel base frame, insulated from the roof of the locomotive, and carrying two rocker shafts, attached to which are the two lower frames. The two upper frames are pin jointed to the lower frames, and to light aluminium castings which carry the collector pans, the whole forming a collapsible pentagonal frame. To secure lightness, the framework is built up from special quality steel tubing, and as a protective device the aluminium castings are designed to break if the pans encounter an obstruction. Rotation of the rocker shafts tends to raise the pantagraph framework, this being actually carried out by admitting compressed air to each of the small cylinders mounted in the base frame, the pistons of which are connected to the rocker shafts. The two outer springs are arranged so that while supporting most of the weight of the frame, they just fail to raise it, and when air pressure has been applied, they combine to give an average pressure of 25 lb. on the overhead wire, a value which varies only 10 per cent over the six feet working range of the pantagraph height. In order to maintain contact with the wire under variations of height as obtained in passing through tunnels, under low bridges and at level crossings, etc., rapid acceleration of the pantagraph framework in an upward direction is necessary, and is obtained by the combination of the light weight involved and the type of springs employed. Actual current collection is carried out by renewable copper or carbon strips fastened on the upper surface of the pans.

Chapter 7

ROLLING STOCK

In describing the various types of rolling stock, tramways and trolley-buses have been dealt with, in addition to the many forms of railway motor-coach and locomotive that comprise the bulk of vehicles coming under this description.

TRAMWAYS

The tramcar body is carried on a steel underframe which extends the full length of the vehicle, this frame being spring-mounted on either a large single bogie of the four wheel type, or on two smaller swivel-mounted four-wheel bogies.

With a two-motor equipment, two alternative methods of motor mounting are available according to the size of the vehicle and the minimum radius of curvature which the car is required to negotiate. With the smaller type body, two-axle construction, each axle carrying a traction motor and gear driven from it, has been used extensively. For larger capacities "maximum traction" trucks, a pair of four-wheel bogies are employed, each bogie having one pair of large driving wheels, whose axle carries the traction motor, and one pair of smaller trailing wheels whose duty is solely to stabilise the bogie. Fig. 117 shows a modern maximum traction truck with the motor mounted in position on the driving axle.

Four motor equipments are always used in conjunction with two four-wheel bogies, all eight driving wheels being the same size and each axle carrying a traction motor.

A driving position is provided at each end of the car, all controls being duplicated, the controllers being conveniently mounted, and, to ensure that both cannot be in operation at the same time, the car has only one master key. In the case of contactor control the master controllers are in the driving positions, while the contactor and reverser groups are mounted in a cabinet located beneath one of the staircases (Fig. 118).

AUXILIARY EQUIPMENT

Auxiliary equipment, such as compressors, air reservoirs and brake gear, is usually mounted on the underframe. The position

FIG. 117 —MAXIMUM TRACTION TYPE BOGIE

(*English Electric*)

of the starting resistance varies with the different coachwork builders, it may be under the staircase or on the underframe. Circuit breakers are within reach of the driver at each end of the car, the standard position being underslung from the cab roof.

COACHWORK

Earlier practice was to use coachwork constructed almost entirely of wood, but of recent years all-metal construction utilising a steel framework covered externally with steel sheeting has been adopted. Three typical examples of modern tramcar construction are shown in Fig. 119.

TROLLEY-BUS

The trolley-bus chassis is constructed on similar lines to that for normal omnibus practice, with either single or double back-axle drive, according to the size and to the seating capacity required. In this country the maximum body dimensions are fixed by the Ministry of Transport, and consequently chassis design has been developed to a few standardised types.

MOUNTING OF EQUIPMENT

The main driving motor is resiliently mounted between the chassis members (usually nearer to one side in order that the motor and back-axle assembly will be clear of the central gangway), transmission being effected through a universally-jointed cardenshaft and a differential back-axle to the road wheels, with a ratio of motor armature speed in revolutions per minute to road speed in miles per hour of between 85 and 90 to 1. When a double back-axle is employed, both sets of wheels are driven through separate differential units with a short universally-jointed shaft between the two axles. In order to ensure even torque distribution to all four rear wheels when uneven inflation or wear of the tyres has occurred, a third differential is fitted between the two axles, and is unit constructed in the foremost axle assembly.

FIG 118—MOUNTING OF TRAMCAR CONTACTOR CONTROL EQUIPMENT UNDER STAIRS

(B T H)

The master controller is mounted beneath the driver's seat, a position which makes for accessibility and simplicity of connection to the power and brake pedals. There are two alternative methods of mounting for the control panel containing the power and shunt field contactors. Where a full cab is provided, this panel is mounted adjacent to the bulk-head at the side of the driver's seat and protected by an asbestos-lined detachable cover. In the case

FIG. 119a.—FOUR-WHEEL DOUBLE DECK SINGLE-ENDED TRAMCAR

(*English Electric*)

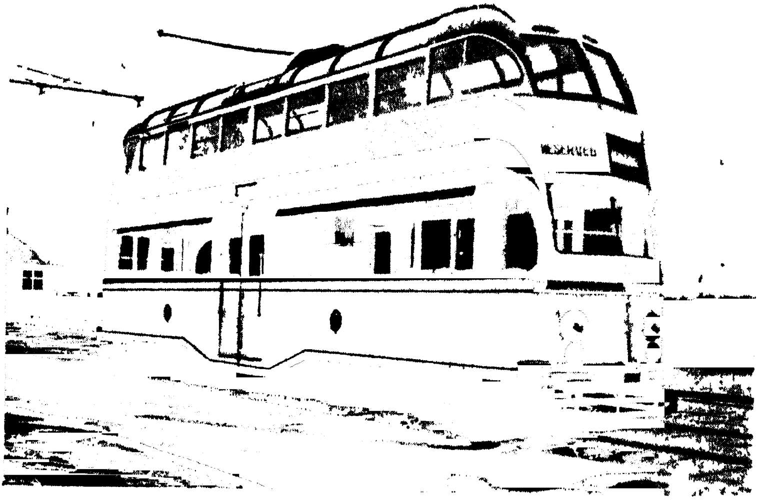


FIG. 119b.—EIGHT-WHEEL DOUBLE DECK TRAMCAR

(*English Electric*)

of a half-cab type body, the contactor cases are mounted on one side of the chassis, and access to them is obtained by means of hinged flaps in the skirt of the body which enable the weatherproof covers to be removed. The main resistances are invariably carried on the chassis, and normally located above or adjacent to the front axle, a position where they obtain the maximum amount of ventilation. Shunt field resistances may be similarly carried, or, in the case of frame-mounted equipment, enclosed in the case housing the shunt field contactors. The combined motor-air compressor unit, together with the reservoir and governor, is carried on the outside of one of the chassis members, and hence all the equipment with the exception of the trolleys and circuit breakers is fitted on the chassis. The circuit breakers are suspended from the cab roof within easy reach of the driver. The trolley base is mounted on, but insulated from, a specially designed framework secured to the body uprights. As the trolley poles are themselves insulated from the base and heads, triple insulation is interposed between the trolley head and the bus body.

The fact that a trolley-bus is insulated from the ground by its pneumatic tyres, makes first-class insulation a vital necessity, and

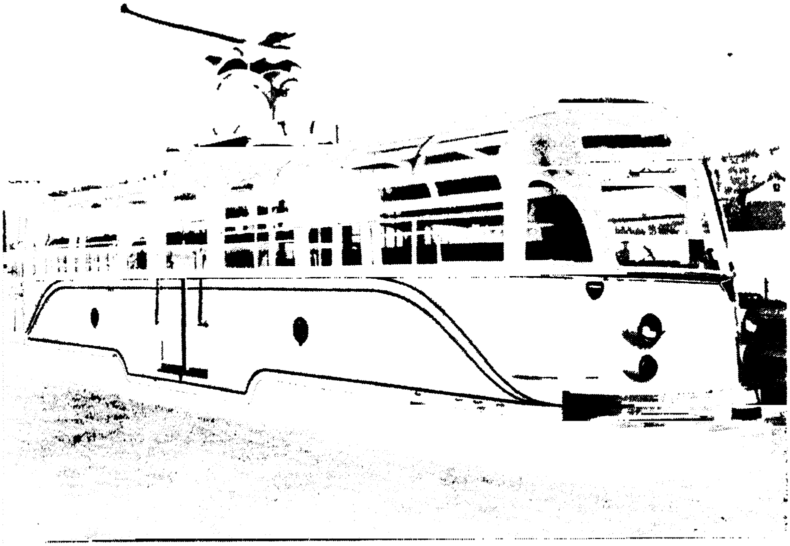


FIG 119c EIGHT-WHEEL SINGLE DECK TRAMCAR

(*English Electric*)

constant exposure to weather and road splash accentuates this point. As regards the motor this does not involve any departure from normal traction practice, class "B" insulation being used throughout. Where control apparatus connected to the power circuit is mounted in cases, the cases themselves are supported from the chassis on insulators in addition to the normal insulation

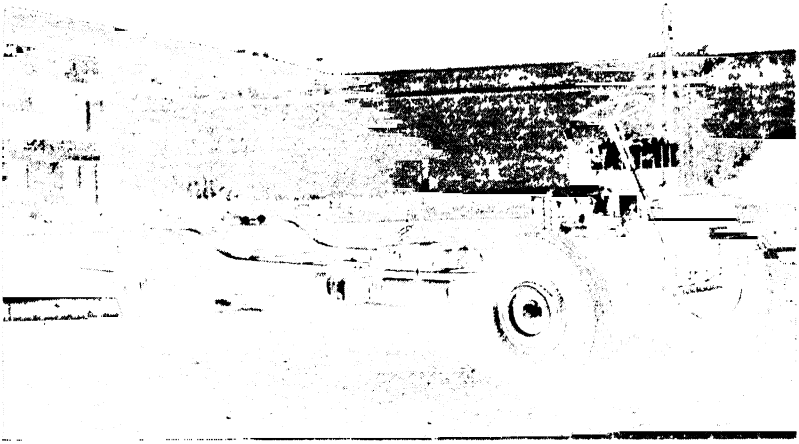


FIG. 120.—FOUR-WHEEL TROLLEY-BUS CHASSIS

(*English Electric*)

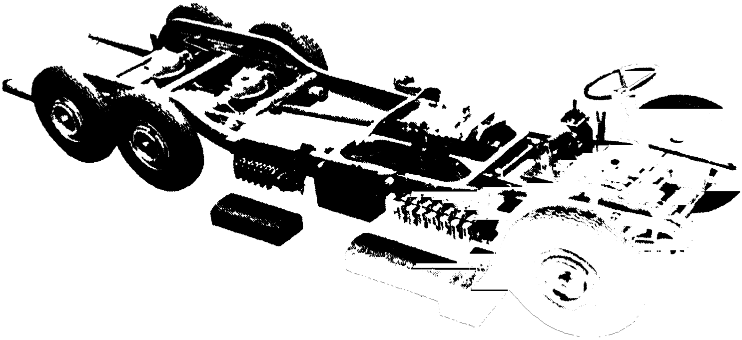


FIG. 121.—SIX-WHEEL TROLLEY-BUS CHASSIS

(*English Electric*)

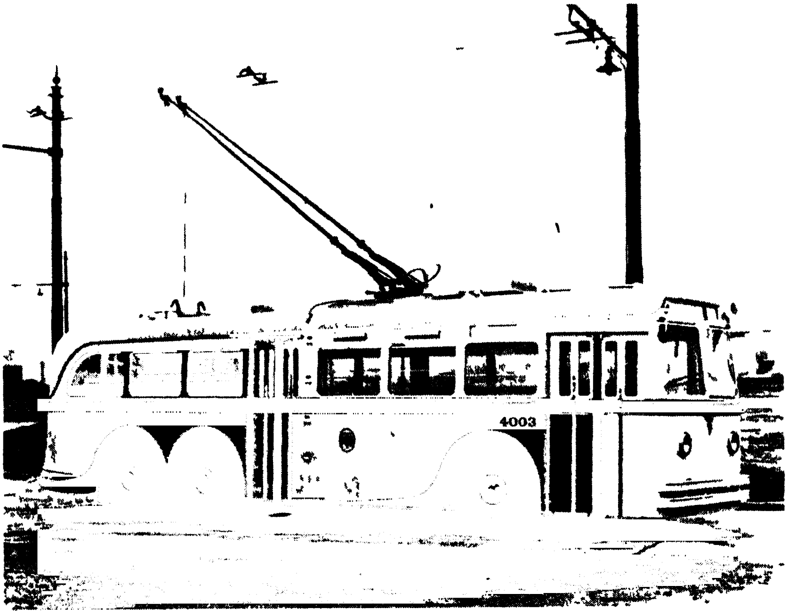


FIG. 122a.—SIX-WHEEL SINGLE DECK TROLLEY-BUS

(*A E C*)

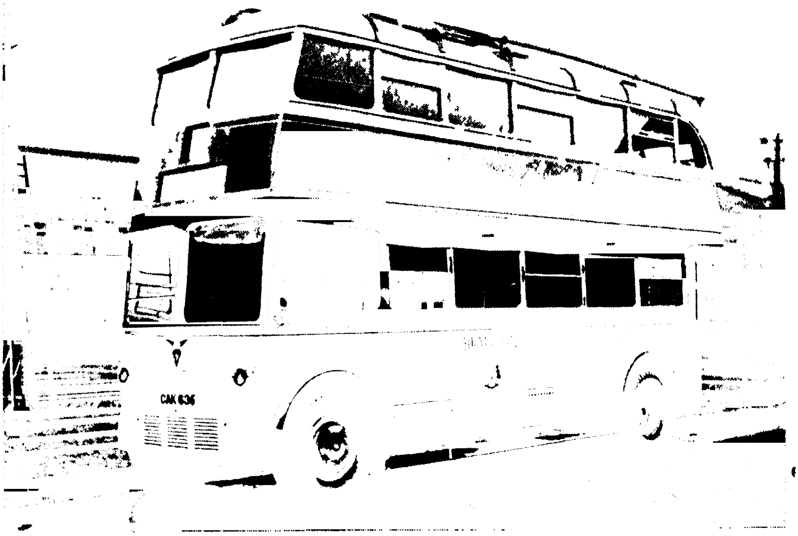


FIG. 122b.—FOUR-WHEEL DOUBLE DECK TROLLEY BUS

(*English Electric*)

on the apparatus itself. Fig. 120 shows a four-wheeled chassis with cab-mounted equipment, the compressor and its auxiliaries being visible on the outside of one chassis member. Fig. 121 shows a six-wheeled chassis with frame-mounted equipment.

COACHWORK

The majority of trolley-buses are constructed with double-decked bodies. Seating capacities range from 30 in the smaller single-decked type to 74 in a three axle double-decked type, and Fig. 122 shows three typical examples of such vehicles. It will be noted that the larger is fitted with a front exit including a staircase for rapid discharge of passengers, an advantage on busy routes. Modern coachwork construction utilises a steel framework, covered externally with steel sheeting and internally by fabric and wood.

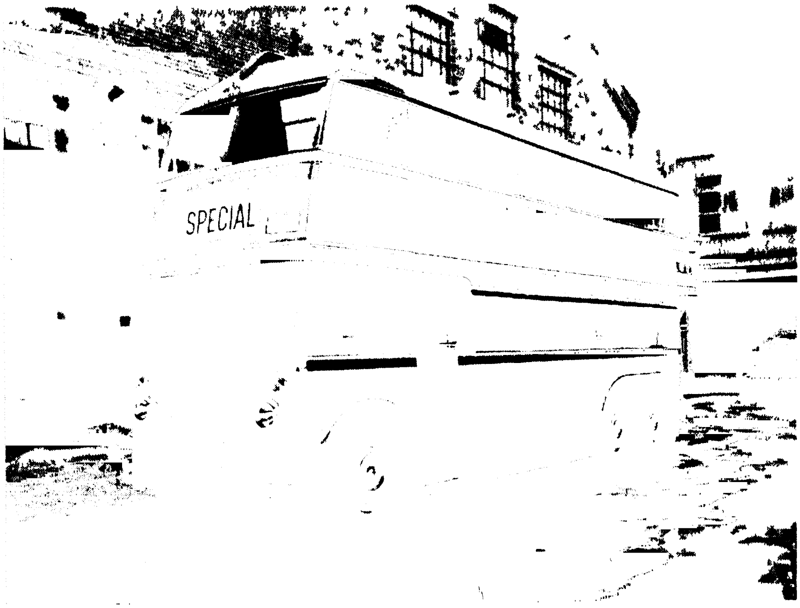


FIG. 122c.—SIX-WHEEL DOUBLE DECK TROLLEY-BUS

(English Electric)

MULTIPLE-UNIT RAILWAY STOCK

As outlined in chapter 1, the electric train set consists of one or two motor-coaches with plain and driving trailers coupled thereto.

FIG. 123.—MOTOR-COACH POWER BOGIE

(*English Electric*)

The motor-coach contains the actual tractive apparatus comprising the traction motors, control-gear and auxiliaries, the methods of mounting these differing considerably according to the requirements of the operating company.

MOTOR BOGIES

The traction motors are axle-hung and nose-suspended from the bogie frame in a manner similar to that employed on four-motor tramcars. When two motors only are employed, it is usual to have a power bogie and a trailing bogie, both motors being installed on the former in preference to having one motor on each. A typical power bogie is shown in Fig. 123; note the compact arrangement of all the apparatus. Single reduction gear drive is almost universal, the actual gear ratios and driving wheel diameters depending upon the service for which the apparatus is designed.

The collector shoes are carried on wooden beams supported by brackets outside the axle boxes of the bogie at each side. Where current return is made through the running rails, brush-gear is fitted in the axle-ways of the motors in order to conduct the current direct to the road wheels without damaging the axle bearings. Insulated return when used is catered for by a central shoe-beam with its appropriate collector-shoe.

Where the traction motors are self-ventilated the cooling air is drawn through louvres in the coach side, filtered, then conveyed through ducts and flexible connections to the motor inlets. This system is employed in order to protect the interior of the motors from dust and weather conditions. Experience has proved that damage to the motor windings is incurred due to penetration of water in the case of directly admitted cooling air.

MOUNTING OF CONTROL EQUIPMENT

To obtain maximum passenger accommodation the whole control equipment, with the exception of the master controller and auxiliary switches, is mounted on the underframe. The contactors, overload and current limit relays, reverser, etc. are grouped together in weatherproof cases, and the main starting resistances are slung from the underframe where ample cooling is obtainable. To reduce the amount of power cabling necessary, these resistances are located as near as possible to the contactors associated with them. The motor-generator set, the compressor and other auxiliaries are also underframe mounted. Fig. 124 shows examples of the mounting of contactor cases, resistance

FIG. 124a.—EXAMPLE OF UNDERFRAME MOUNTING

(*English Electric*)

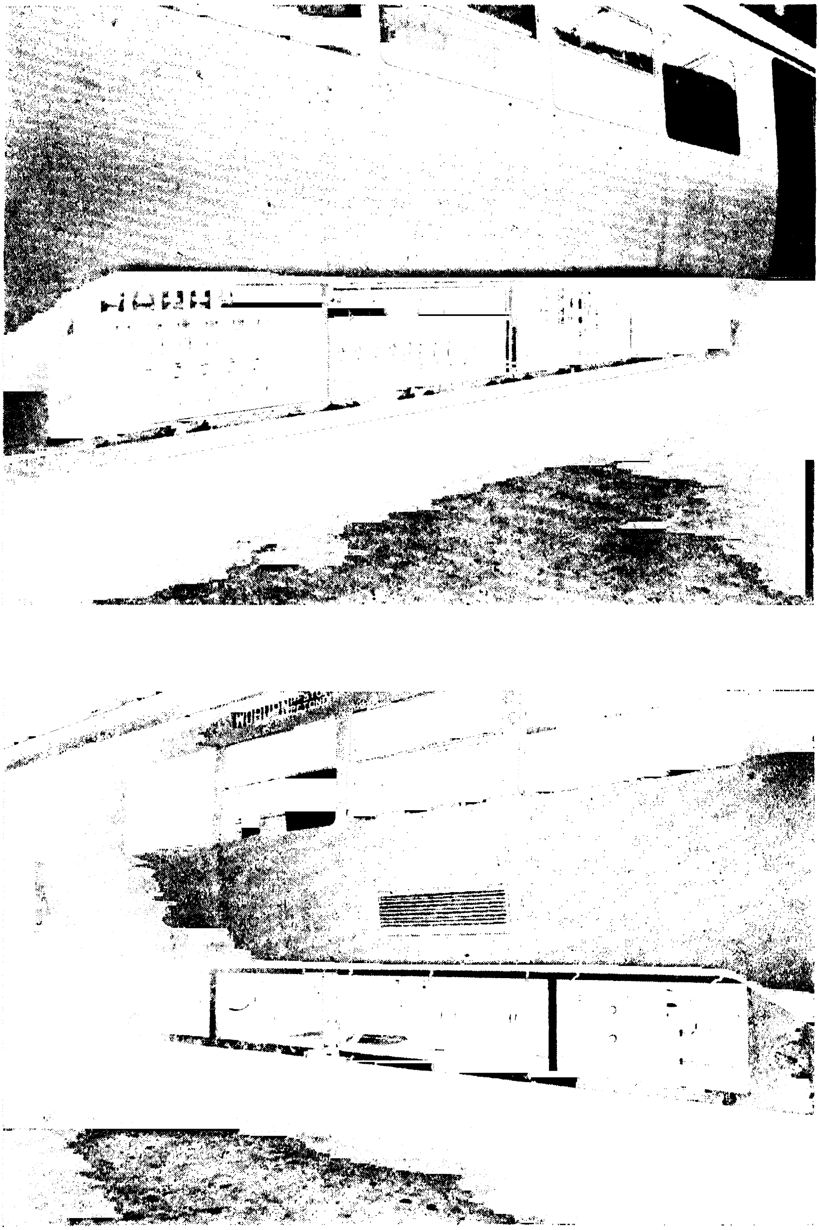


FIG. 124b and c.—FURTHER EXAMPLES OF UNDERFRAME MOUNTING
(*English Electric*)

boxes and auxiliary equipment on various motor-coach underframes. In the first illustration the motor-coach concerned has four motors controlled in two entirely separate groups, the contactor cases for one group only being shown mounted side by side.

Where insufficient space is available to allow underframe mounting, or where climatic conditions are unsuitable, the equipment may be situated in a separate compartment adjoining the driver's cab, and accessible from it by a door. Interlocking is sometimes provided so that all the control gear must be isolated before the door can be opened. The apparatus is frequently grouped at each side of a central gangway.

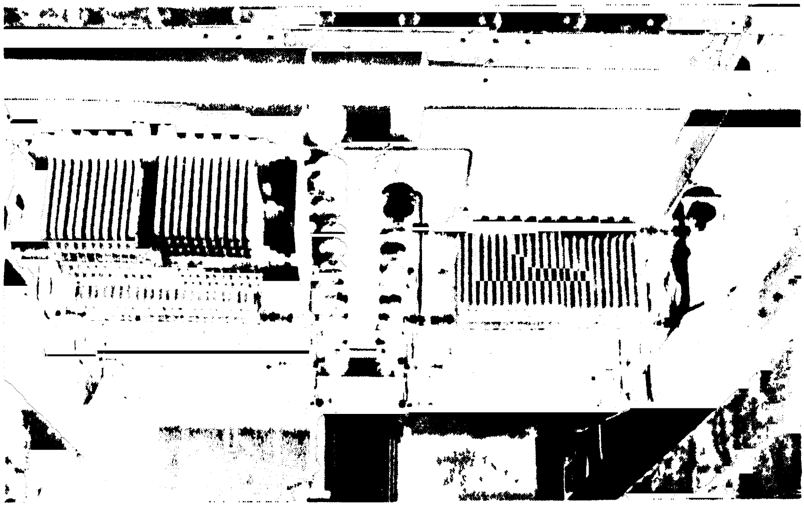


FIG. 124d.—EXAMPLE OF UNDERFRAME MOUNTING

(*Metro-Vickers*)

A driving position is provided at the leading end of each motor-coach, and in addition on certain selected trailer coaches, known as "driving trailers". The actual arrangement of the driver's cab differs in a driving trailer from that in a motor-coach. In the latter the master controller and driver's brake valve are mounted adjacent to the driving window, whilst the control switches, compressor and motor-generator contactors, voltage regulator, fuses, etc. are all enclosed in a cupboard on the rear bulkhead of the driving cab. Only the master controller, brake valve and control switches are installed in a driving trailer cab.

FIG. 125.—CAB-MOUNTED CAMSHAFT EQUIPMENT

(*English Electric*)

A control train-line runs throughout the length of the train, and consists of a multi-core cable passed from coach to coach by means of multi-way plugs, sockets and jumpers, access being obtained to it by means of connection boxes in the driving and main equipment positions. Each master controller is connected to this train-line, and all main equipments are fed from it for control purposes, hence any controller may be used to operate the whole train.

COACHWORK

As with other types of passenger transport vehicle, modern motor-coach stock is of all-steel construction giving a semi-streamlined effect. Interior layout varies considerably with the class of traffic to be catered for. Where a very dense short-distance traffic is encountered, the design of the coachwork must be such as to allow rapid loading and unloading of passengers in order to avoid excessive station standing time. Two types of stock fulfil these requirements, one is compartment stock, in which each coach is divided into from eight to ten separate compartments, each seating twelve passengers and being entered through its own door. This type is already in normal use on many steam-operated suburban services. Alternatively open saloon type construction with a central gangway and side seating either longitudinally or transversally may be employed; a system which, while reducing the seating capacity by thirty per cent, provides a relatively large standing area. Central doors of the sliding type give easy access to the interior, and are frequently arranged for automatic operation, using electro-pneumatic control from the drivers' and guards' compartments. In this case interlocking is provided between the doors and the master controller to ensure that the train cannot be started until all doors are closed. A good example of the use of the latter type of stock may be seen on the London Underground services.

FIG. 126.—MOTOR-COACH DRIVING CAB
(*English Electric*)

On longer distance and express trains the usual standard vestibule type of coach is used, including both side and central corridor construction. The motor-coach is usually of the composite type comprising driver's cab, guard's and luggage compart-

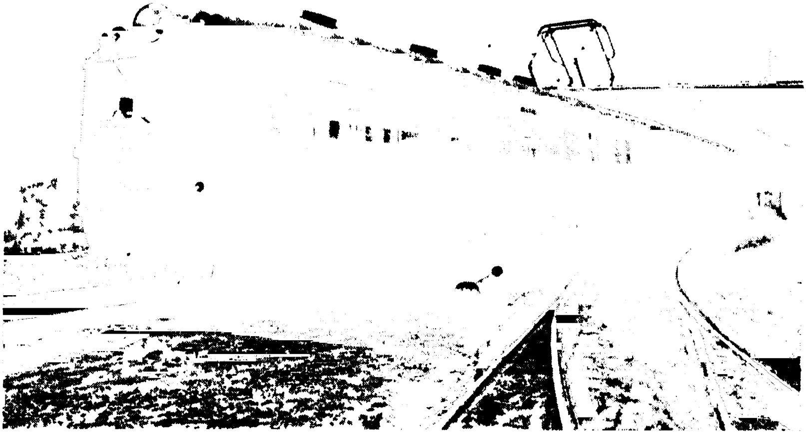


FIG. 127.—TYPICAL MOTOR COACH AND DRIVING TRAILER

(English Electric)

ment and some four or five passenger compartments. Other types of coach layout are largely confined to trailer coaches.

Where restaurant and buffet cars are required, electrical facilities are usually provided. Power is obtained from the train-line to drive a motor-generator set mounted on the kitchen car underframe. The low tension output at 100 to 200 volts then supplies the various electrical apparatus.

MAIN-LINE LOCOMOTIVES

In electric locomotive practice, the control gear is always accommodated in the locomotive body, as no useful purpose would be served by underframe mounting even if sufficient space were available. In the majority of applications the whole of the space below the locomotive frame is taken up by either the traction motors themselves, where these are axle-hung, or by the mechanical transmission system when the motors are frame mounted.

Locomotive designs, and the layout of their equipments vary considerably, consequently descriptions of typical locomotives,

FIG. 128.—G.I.P. RAILWAY ARTICULATED FREIGHT LOCOMOTIVE
(*Metro-Vickers*)

designed for various duties and operating on different systems, will serve to illustrate the general principles involved.

HEAVY FREIGHT LOCOMOTIVE

The locomotive illustrated in Fig. 128 is one of forty-one such locomotives supplied to the Great Indian Peninsular Railway for operation of freight traffic on the steeply graded Bombay-Poona and Bombay-Igatpuri sections. The maximum speed is 45 m.p.h. and with a weight of 120 tons, a tractive effort of 56,000 lb. at 18 m.p.h. is obtainable on the one hour rating of the motors. The locomotives are articulated in that the two six-wheeled driving bogies support the body on pivots at each end. Each driving bogie has six coupled wheels four feet in diameter and driven from a jackshaft by connecting rods. Mounted side by side on each bogie are two 1,500 volt 650 h.p. traction motors (Fig. 129), having single-helical pinions at each end of their armature shafts, these four pinions driving two common gear wheels mounted on the jackshaft. The motors are forced ventilated, each having its own blower, the two blowers on one bogie being driven by a single motor. A certain amount of control apparatus, used for reversing and field control, is also carried on the bogie in order to reduce to a minimum the number of cables passing between the hinged bogie and the body itself. The whole bogie equipment is surmounted by a large removable hood, in the sides of which are louvres for the intake of cooling air to the blowers. This arrangement of motors, etc., greatly facilitates access for maintenance purposes, which can be gained if necessary by the small door, visible on the left of the illustration (Fig. 130), in the event of the hood being in position.

The current collecting gear, consisting of two pantagraphs, is mounted on a false roof, itself mounted on insulators attached to the main roof, although as a rule only one pantagraph is in use at a time.

Double series-parallel control with field tapping and regenerative braking serves to give six economical running speeds and good control of the train when descending steep gradients. A driving position is situated at each end of the main body, and the high tension control gear housed in a chamber which is only accessible when the 1,500 volt supply is disconnected. A portion

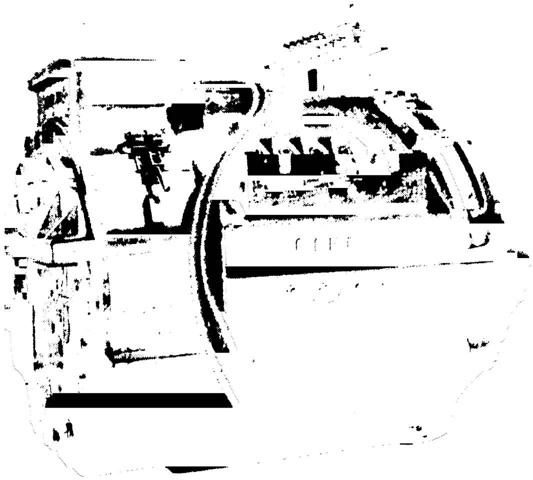


FIG. 129.—650 H.P. LOCOMOTIVE MOTOR

(*Metro-Vickers*)

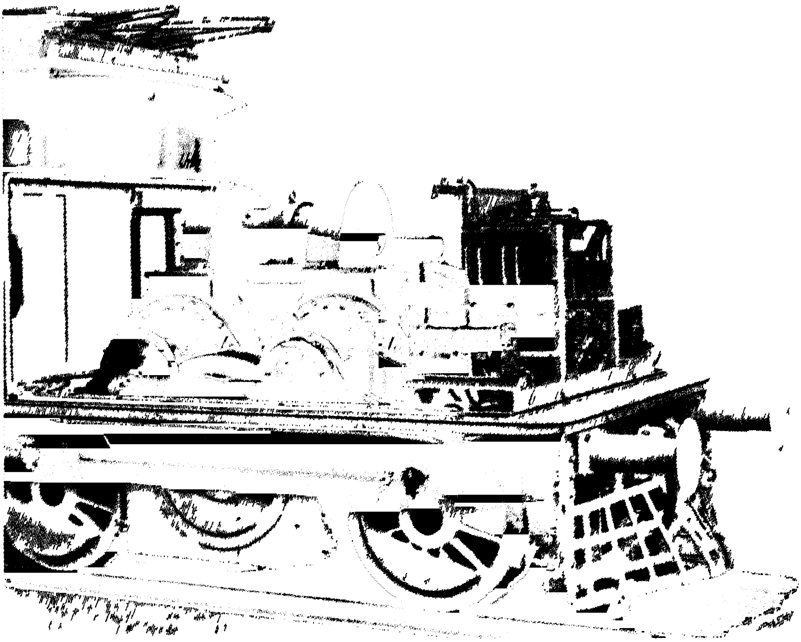


FIG. 130.—DRIVING BOGIE—G.I.P. FREIGHT LOCOMOTIVE

(*Metro-Vickers*)

of this high-tension chamber is shown in Fig. 131, the electro-pneumatic contactors and their interlocks being visible at the top of the illustration on each side, the control terminal bars and isolating switches at the back with various fuses beneath them, and the motor combination and motoring-generating cam groups at the bottom left.

The main starting resistance is located in an annexe to the high-tension compartment, accessible from it through a sliding door. This chamber is very well ventilated, having air inlets in the floor and sides so that a draught is created due to the hot air rising and passing out through the ventilators in the roof.

Excitation for regenerative braking is obtained from two axle-driven generators, one on each bogie and, as braking can be carried out in any of the three motor combinations, effective braking is obtained at speeds varying from 8 to 35 m.p.h.

Compressed air brakes on the locomotive and vacuum brakes on the train are both controlled from one driver's brake valve, which operates the vacuum brake directly and the compressed air brake by means of a proportional valve. Two exhausters and two compressors are included in the equipment to give the necessary supplies to the braking apparatus.

MIXED TRAFFIC LOCOMOTIVE

The locomotives illustrated in Fig. 132 are three of the 1,200 h.p. multiple control units built for the Pietermaritzburg-Glencoe-Durban section of the Natal Railways, South Africa, whose power and control schematic diagrams are illustrated and described in chapter 4. Each unit weighs 69 tons and has four 300 h.p. 1500 volt motors working as two pairs connected in permanent series from a 3000 volt supply. Operating in units of three, these locomotives maintain an average speed of 21 m.p.h. with a 1,500-ton train on a gradient of 1 in 65, exerting a tractive effort of 63,600 lbs. at this speed, which corresponds to the one hour rating of the traction motors. As will be seen from the

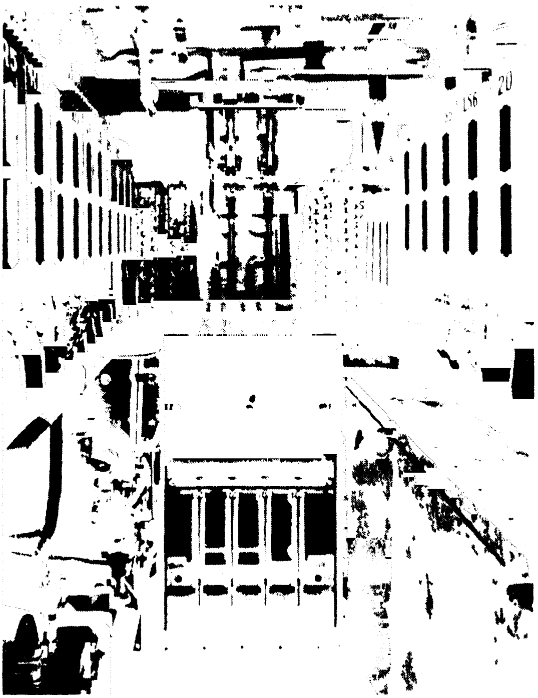


FIG. 131.—H.T. COMPARTMENT—G.I.P. FREIGHT LOCOMOTIVE

(*Metro-Vickers*)

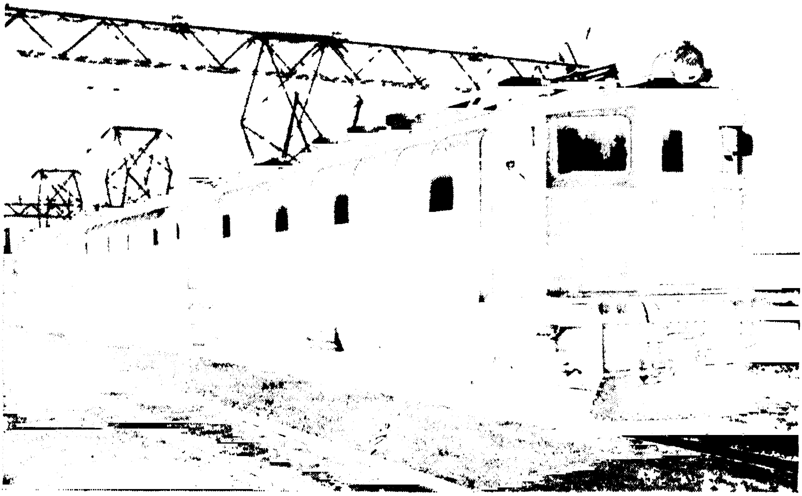


FIG. 132.—S.A.R. MULTIPLE UNIT LOCOMOTIVES

(Metro-Vickers

illustration, the locomotives are of the double bogie type, the four motors being axle-hung and nose-suspended as with motor-coach stock. A driving cab (Fig. 133) is provided at each end of all units, and access between units is by means of a door alongside the driving position. A side corridor connects the two driving cabs in each locomotive together, with two groups of auxiliary machinery separated by the high-tension compartment opening from it. Fig. 134 shows the interior of this high-tension compartment. The main line-breakers are at the right-hand end of the upper row of contactors, and the drum-type reversers and change-over switches at the centre bottom.

DOUBLE BOGIE PASSENGER LOCOMOTIVE

The locomotive illustrated in Fig. 135 is of the 2–6–0 + 0–6–2 wheel arrangement comprising two bogies each with three driving axles and a pony-truck. Six 390 h.p. 1,500-volt motors, operated in series-connected pairs from the 3000 volt line, give a maximum tractive effort of 44,000 lb., and make the locomotive capable of a speed of 60 m.p.h. The motors are axle-hung and drive through single reduction gearing, forced ventilation being employed with the two blowers driven from the motor generator sets. Control gear is mounted in the usual high-tension chamber.

HIGH SPEED PASSENGER LOCOMOTIVE

This passenger locomotive (Fig. 136), is one of those employed by the Great Indian Peninsular Railway on the same section as the freight locomotive described earlier in this chapter. It weighs 100 tons, develops 2,160 h.p., is capable of a maximum tractive effort of 33,600 lb. and a maximum speed of 85 m.p.h. The wheel arrangement comprises three pairs of driving wheels with a pony-truck at one end and a four-wheeled bogie at the other. Six 750-volt driving motors are mounted in pairs over the three axles, each pair driving on the Winterthur Universal principle through an intermediate gear to a hollow gear wheel surrounding the road axle, but carried in bearings on the locomotive frame itself. A floating connection which allows axle movement relative to the gear wheel is employed to transmit the drive from the gear to the axle.

FIG. 133.—DRIVING CAB OF S.A.R. MULTIPLE UNIT LOCOMOTIVE

(*Metro-Vickers*)

Double series-parallel control, operated electro-pneumatically, is used, in which motor combinations are arranged to give six

FIG. 134.—H.T. COMPARTMENT OF S.A.R. MULTIPLE UNIT LOCOMOTIVE
(*Metro-Vickers*)

motors in series, two circuits of three motors in series, and three circuits of two motors in series. As a field tapping can be used with any of these three combinations, six economical running speeds are obtainable. Regenerative braking is not required on these locomotives.

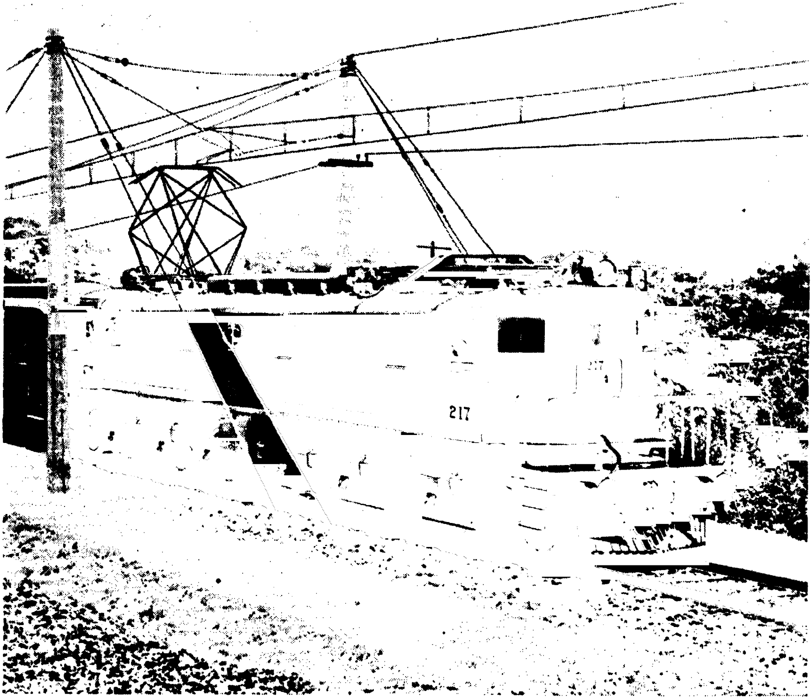


FIG. 135.—$1-C_0+C_0-1$ PASSENGER LOCOMOTIVE

(*Metro-Vickers*)

The layout of the frame-mounted motors is such that a central gangway is necessary, and the control apparatus is consequently carried on frames at either side, interlocking doors being fitted to prevent access when the gear is alive. Adjoining one of the driving cabs is the auxiliary machine compartment, containing the compressor, exhauster, blowers, etc., and in a similar position at the opposite end of the locomotive are the main starting resistance boxes.

BRITISH MIXED-TRAFFIC LOCOMOTIVE

Up to the present day the use of electric locomotives in this country has had a very limited application, only two lines having employed electric locomotives to any extent, the Metropolitan Railway and the former North Eastern Railway on its Newport-Shildon section. In 1938, however, the London and

North Eastern Railway decided to electrify all the traffic between Manchester, Sheffield and Wath, a line which carries a very heavy coal traffic between the South Yorkshire coalfield and South-East Lancashire and Cheshire. The route passes through the Pennines by means of the three-miles-long Woodhead tunnel, which is approached from both the Manchester and Sheffield ends by long and continuous gradients. Some 70 locomotives were scheduled for construction to operate both passenger and freight trains, but up to the present only the first has been completed.

This locomotive is illustrated in Fig. 137; it is of the double-bogie type fitted with four axle-hung traction motors. The two bogies are articulated together and carry the buffers and draw-gear, so that the actual drawbar pull is exerted through the bogie frames and not through the main frames. The bogies with the motors mounted in position are shown in Fig. 138. As the locomotive develops 1,850 h.p. at the one hour rating of the traction motors, multiple-unit operation was not thought to be necessary for normal traffic requirements, so that in the event of two locomotives running coupled together, each locomotive must carry its own driving crew.

A side corridor connects the two driving cabs together, and opening from it are five chambers in the following order; one motor-generator-blower compartment, main starting resistance compartment, high tension compartment containing electro-

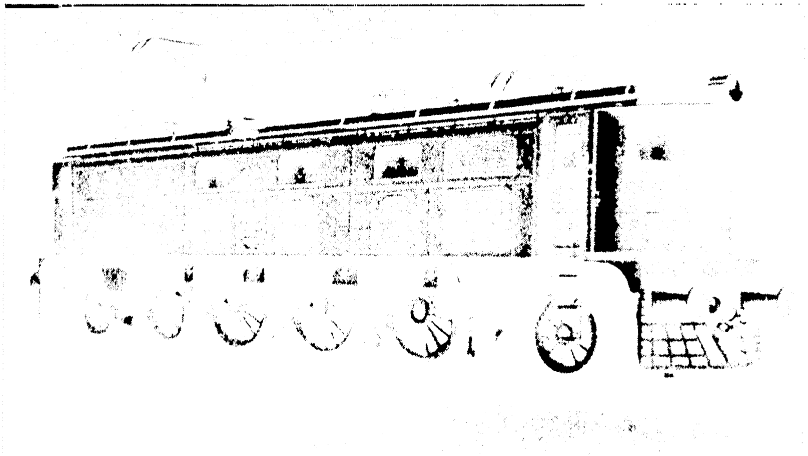


FIG. 136.—PASSENGER LOCOMOTIVE WITH WINTERTHUR DRIVE
(*Metro-Vickers*)

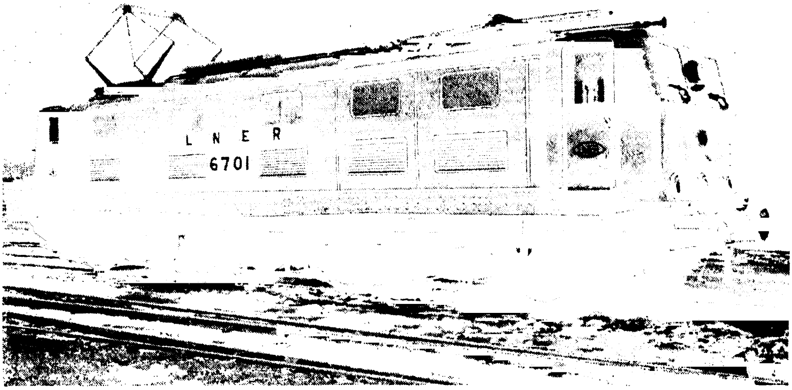


FIG. 137.—L.N.E.R. MIXED-TRAFFIC LOCOMOTIVE
(*L.N.E.R.*)

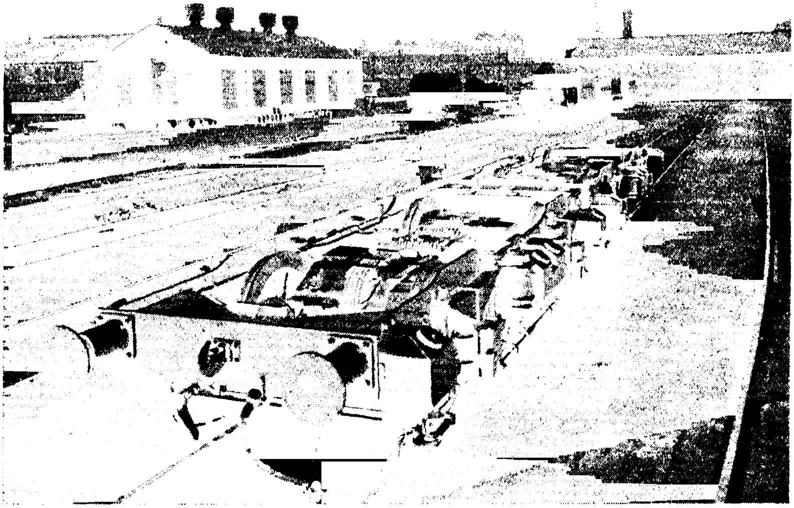


FIG. 138.—MOTORS AND BOGIES OF L.N.E.R. MIXED-TRAFFIC LOCOMOTIVE
(*L.N.E.R.*)

pneumatic contactors, reverser, overload relays etc., boiler compartment, and the second motor-generator-blower compartment. The partly-built locomotive is shown in Fig. 139 in which this layout can be clearly seen.

An electrically-heated boiler is to be fitted on twenty of the locomotives for train-heating purposes, and as far as possible, passenger train working will be confined to this group.

MIXED-TRAFFIC RIGID-FRAMED LOCOMOTIVE

The locomotive illustrated in Fig. 140 is one of a series of eight built in 1938 for operation of the steeply-graded and tunnel section of the New Zealand Government Railways main line between Wellington and Paekakariki, a distance of 24½ miles.

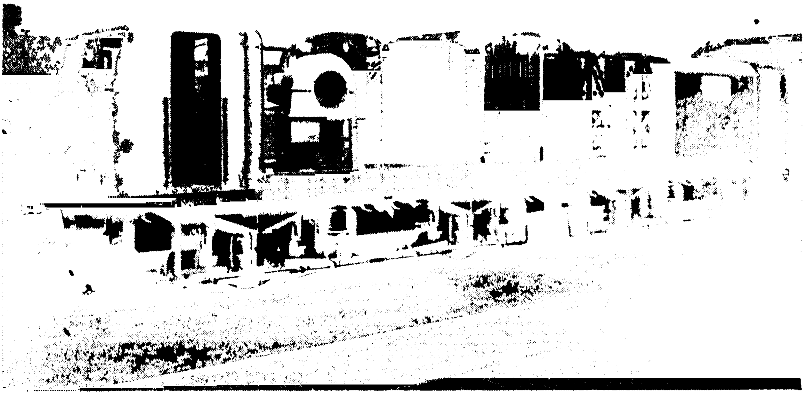


FIG. 139. LOCOMOTIVE WITH SIDE SHEETINGS, ETC. REMOVED
(*L.N.E.R.*)

The driving axles run in roller bearings, and the drive is transmitted from the traction motors which are frame-mounted by the quill and cup system, the hollow quill shaft being carried in bearings cast integral with the motor frame. This provides the necessary flexibility to allow for the springing of the axles. A photograph of the motor, with the quill shaft, cups, and driving wheels is shown in Fig. 37. As the gauge of the track is 3 ft. 6 in. and there is a severe limitation in the loading gauge over the section, it was necessary to employ a driving wheel diameter of 3 ft. 9 in., probably the smallest size of wheel to which the quill and cup has been applied. The wheel arrangement is 2–8–4, the four-wheeled bogie being provided to permit an extension of the locomotive frame at one end necessary to accommodate an automatic oil-fired boiler for train-heating purposes.

A maximum tractive effort of 44,000 lbs. is provided by the four traction motors, one driving each axle, an output of 310-h.p. per motor being obtainable at the one-hour rating. Cooling of the motors is effected by forced ventilation using two blower-units each supplying a pair of traction motors, this arrangement being clearly shown in Fig. 141.

Electro-pneumatic contactor type control is used, each pair of motors being connected in permanent series. Power is supplied at 1500 volts, and, by the use of series-parallel control with two field tappings at each position, six economical running speeds with a maximum of 55 m.p.h. are available. Multiple-unit operation is provided for, six train-line coupler sockets being visible just beneath the driving cab windows. Two interesting devices are incorporated in the equipment, these are the "current limiter" and the "wheel slip relay". The former, as distinct from a circuit breaker, operates on the rate of rise of current and,

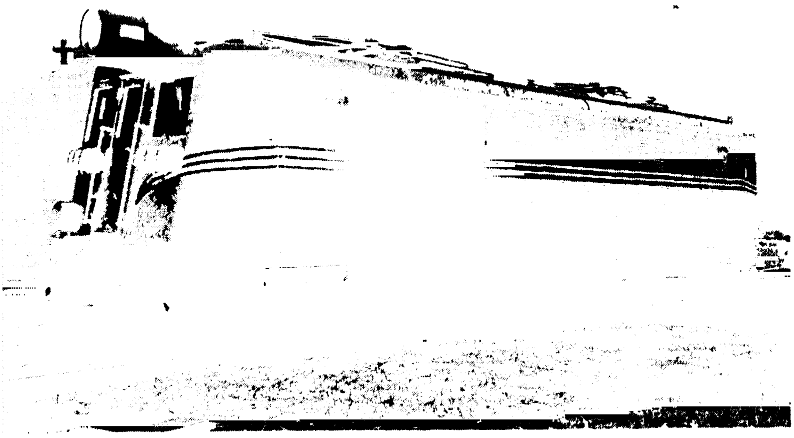


FIG. 140.—2–D_0–1 MIXED-TRAFFIC LOCOMOTIVE

(English Electric)

FIG. 141. H.T. COMPARTMENT OF MIXED-TRAFFIC LOCOMOTIVE
(*English Electric*)

in the event of a fault, inserts a resistance in the circuit and then causes the line-breakers to open, the advantage of this arrangement being the rapid action, which prevents the fault current from rising to an excessive value, hence keeping the duty of the line-breakers within reasonable limits. A wheel slip indicating relay is connected across the armatures of each pair of series-connected motors and any voltage out-of-balance due to one pair of wheels slipping causes the relay to operate and light a signal lamp in the driving cab.

The main starting resistances are mounted at one side of the locomotive and, by an arrangement of ventilators in the floor and roof, a self-induced draught ventilating system is provided. At the opposite side of the high-tension chamber, all contactors and relays are mounted on an angle-iron framework so that one side of them is accessible from the interior and the other through interlocked doors from the corridor which runs down the side of the locomotive and connects the two driving cabs. The interior of the main high-tension compartment with the main resistance chamber covers removed is shown in Fig. 141. The motor generator set and one compressor are located one above the other at the boiler end, and the second compressor and current limiter at the opposite end of the high-tension compartment.

Fig. 142 shows one driving cab of the locomotive and demon-

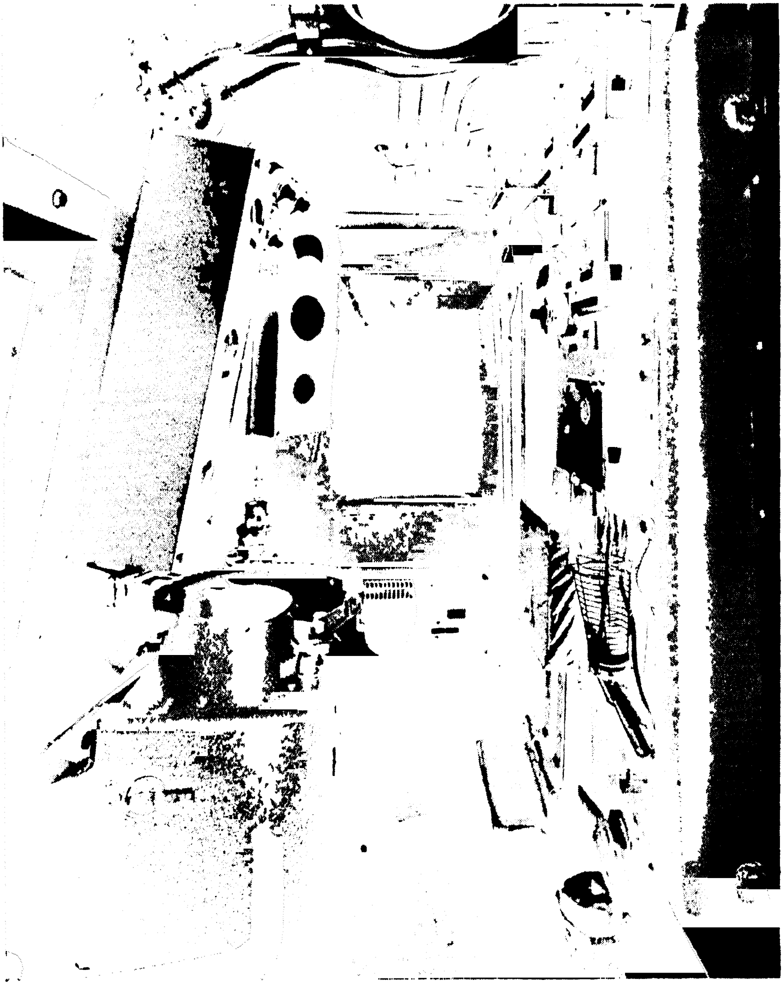


FIG. 142.—DRIVING CAB OF MIXED-TRAFFIC LOCOMOTIVE

(*English Electric*)

FIG. 143.—1000 H.P. SHUNTING LOCOMOTIVE

(Metro-Vickers)

strates the convenient arrangement of the various control switches which enable the driver to handle the locomotive with the minimum of fatigue.

SHUNTING LOCOMOTIVES

When complete electrification of a railway system is carried out, it is necessary to provide electric shunting locomotives for marshalling yard duties. These are usually of the double-bogie type, employing up to four traction motors with a total output of between 500 and 1,000 h.p.

The locomotive illustrated in Fig. 143 is of this type, being designed to operate on a 1,500 volt supply. Four 250-h.p. motors are mounted in pairs on the two bogies, each pair being permanently connected in series. Electro-pneumatic control is used, and together with field tappings on the motors, provides four economical running speeds. Provision is made for multiple-unit working.

On account of the frequent reversals required in shunting work, a central driving cab is provided and flanked on each side by two equipment compartments which contain the control gear, main starting resistance, motor-generator-blower set and battery.

The locomotive is designed for a maximum speed of 32 m.p.h., and exerts a tractive effort of 20,500 lb. at 16 m.p.h.

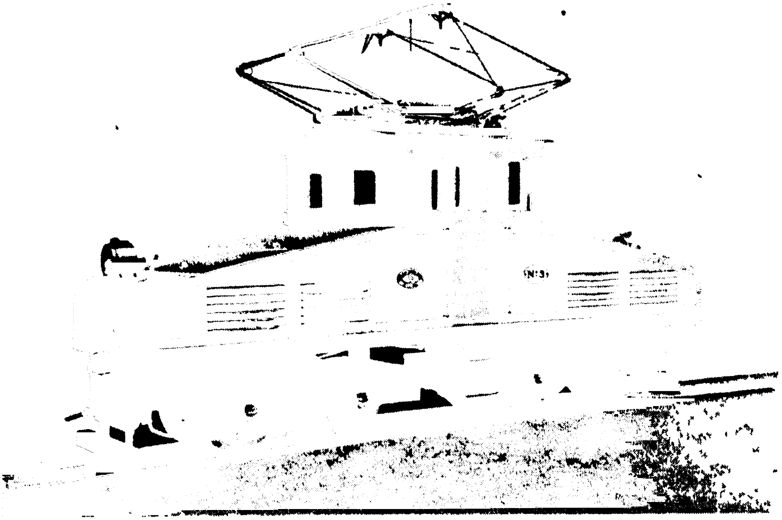


FIG. 144.—PANTOGRAPH BATTERY LOCOMOTIVE

(*B.T.H.*)

INDUSTRIAL LOCOMOTIVES

Electric haulage in the industrial field is not restricted to any one particular type of locomotive. There are two main groups, the first being those carrying their own power supply, and the second, those obtaining their supply from an external source.

BATTERY LOCOMOTIVES

The former type are chiefly battery locomotives, being designed for operation where it is impracticable to use any form of current collection, such as in mining applications, certain chemical works, etc. The battery, which may be anything from 60 to 500 volts in output, is carried on the locomotive frame to increase the adhesive weight, or if this arrangement is unsuitable, towed behind the locomotive on a battery tender. Acid or alkaline type batteries may be used, the latter being preferable for most purposes. Locomotives for mining service, when of the battery-powered type, are frequently fitted with flame-proof motors and control gear, to avoid any possibility of arcing in the system causing a fire or explosion.

FIG 145a —BATTERY OPERATED MINING LOCOMOTIVE (*B T H*)

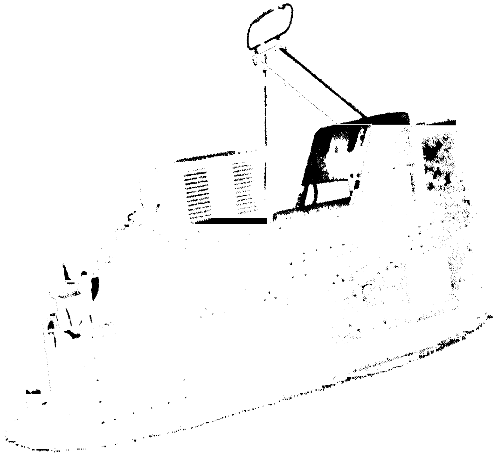


FIG 145b —OVERHEAD COLLECTION MINING LOCOMOTIVE (*English Electric*)

EXTERNAL SUPPLY

Locomotives which operate from an external supply may collect the power from either a third rail or from an overhead wire, in the latter case employing either a trolley, bow collector or pantagraph, supply voltages between 250 and 600 being normal. Certain cases occur where the locomotive is required to work for short periods away from its power supply line, in which case, *either* a battery is fitted in addition to the normal collection apparatus, this battery being on charge when operating from the external supply, *or* a cable reel employed, the cable being attached to the source of power, laid behind the locomotive as it moves away and re-wound as it returns.

In general a locomotive equipment consists of two or four traction motors with their associated control gear and starting resistances. Standard axle-hung motors are employed, the drive being taken through spur gearing, except in certain special cases where worm-geared motors are used on narrow-gauge systems.

CONTROL GEAR

Control is normally by the series-parallel system, and in all smaller locomotives a direct controller as shown in Fig. 55 and described in chapter 3, is utilised. Where the power involved is beyond the capacity of such a direct controller, indirect control with electro-magnetic or electro-pneumatic contactors and a master controller is adopted. Where the latter method is employed, a compressor is necessary, and consequently a direct air brake is frequently incorporated in the equipment. Most operating companies require the inclusion of "dead man's" protection, which takes the form of a handle or pedal arranged to trip the main circuit-breaker when released. Figs. 144 and 145 show typical examples of industrial locomotives.

Chapter 8

DIESEL-ELECTRIC TRACTION

A DIESEL-ELECTRIC locomotive or train set combines the flexibility of an electric drive with that of complete mobility on any existing system without any modification to that system being necessary, this being due to it carrying an independent power unit.

The principle of the system is that of supplying the power for the traction motors by means of a diesel engine-driven generator. The voltage applied to the former is varied by regulating the engine speed and the generator exciting current, thus eliminating the use of starting resistances. In multiple unit coaching stock, several engine-driven units are controlled from one master controller through a control train-line.

Four types of diesel-electric unit are used in normal railway practice:—

(*a*) The main-line diesel-electric locomotive, which may contain engines up to 2,000 h.p. each, and be capable of speeds up to 100 m.p.h.

(*b*) The diesel-electric shunting locomotive, with an engine of 300 to 500 h.p., and a maximum speed of 15 to 30 m.p.h.

(*c*) Diesel-electric multiple unit coaching stock, where each motor-coach has an engine of 180 to 200 h.p., and the train set is capable of a speed of 50 to 70 m.p.h.

(*d*) The diesel-electric railcar, with an engine of 100 to 600 h.p. which may operate as a single car or in conjunction with one or more trailers.

POWER LIMITATION

As it is important that the engine should not be overloaded, some form of power demand limitation must be introduced. The ideal system is to utilise a generator having a characteristic which approximates closely to the engine output curve. This is done by providing suitably designed field windings so that the output of the generator (and hence that of the engine) cannot exceed a predetermined amount. Such a generator will protect all the electrical equipment, and in particular the traction motors, against excessive currents and voltages.

ENGINE-DRIVEN GENERATORS

The following principles apply to the generators of all the diesel-electric units described in this chapter.

Generator frames are either cast or more often fabricated, and utilise a field system of at least six poles. The increased number of poles are used in order to keep the relative length of the armature core and commutator as short as possible for a given output, and at the same time provide a machine suitable for low speed running at 300 to 800 revolutions per minute. The large diameter frame is advantageous from the point of view of the overhung mounting, housing of the brush gear, and accessibility of both brush gear and commutator for maintenance purposes.

GENERATOR OUTPUT CONTROL

Two methods of generator output control are available, and these may be used either combined or separately. The first method is that of varying the engine speed, and may be accomplished by using several fixed running speeds, or by a continuous speed range controlled by a throttle. Secondly the excitation of the generator may be controlled by the insertion of resistance into its field circuit, or indirectly by control of the exciter voltage. Determination of the generator characteristic to be used is therefore governed by the control system chosen. A combination of both methods is used for shunting locomotives, where constantly varying duties exist, demanding different values of tractive effort, rates of acceleration and running speeds. Fig. 146 shows typical characteristics of a generator suitable for such work. The main field excitation is provided by two independent shunt windings, one self-excited from the

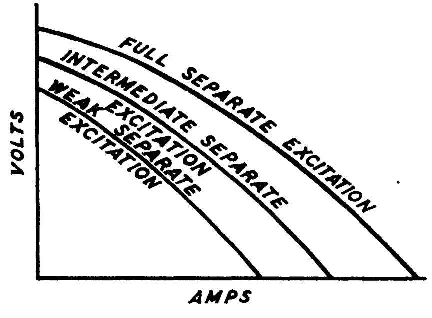


FIG. 146.—LOAD CHARACTERISTICS OF SEPARATELY-EXCITED SHUNT GENERATOR FOR DIESEL-ELECTRIC SERVICE

generator terminals, and the other separately excited from a low tension auxiliary generator, working in parallel with a battery. Design of the field system is such that a drooping voltage curve is obtained with increasing load current, so enabling the traction motors to be connected across the generator terminals without resistances to limit the applied voltage during starting and acceleration.

Two distinct methods of obtaining the required generator characteristics are used. An outline of the electrical principles involved follows.

SELF-EXCITED GENERATOR

Referring to page 23 from the paragraph on self-excited generators, it is seen that the conditions for self-excitation are those where the field resistance line lies below the field magnetisation curve. In this case the total resistance of the self-excited field circuit is adjusted by an external rheostat, so that the resistance line is above the magnetisation current curve, and therefore no building up occurs. By applying a separate excitation from the battery, the magnetisation curve is raised with consequent building up of the generator voltage. In this manner an appreciable total number of field ampere-turns can be obtained by the application of a relatively small battery-excitation current, the ultimate field strength being proportional to the value of the battery field.

Working with a value of field flux considerably below saturation point, as the armature current increases, the armature ampere-turns, by neutralising those of the main field, cause a corresponding fall in generator volts, and likewise in self-excitation. Ultimately a point is reached where the battery field only is effective in producing generated e.m.f. This being relatively low with heavy armature currents, it is mostly absorbed in armature resistance drop. Thus

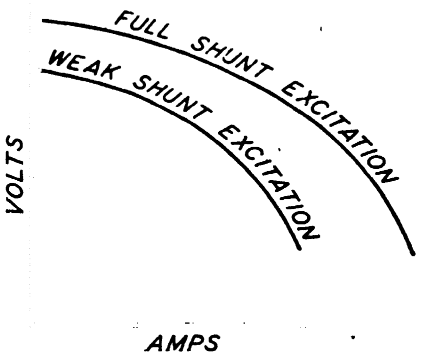


FIG. 147.—LOAD CHARACTERISTICS OF SERIES DECOMPOUNDED GENERATOR FOR DIESEL-ELECTRIC SERVICE

the voltage applied to the traction motor is automatically adjusted according to its current and hence to its speed.

SERIES DECOMPOUNDED GENERATOR

The second type of generator, in use most successfully on power units for railcars and multiple-unit motor-coach stock, is the series decompounded machine, characteristics of which are shown in Fig. 147. The field system is of the six-pole type, each main pole being fitted with a composite coil consisting of a separately excited shunt winding and a series winding carrying the armature load current, so wound as to decompound the shunt turns. Separate excitation current for the shunt winding is provided directly by a low tension auxiliary generator.

The control system gives a series of engine running speeds with a constant exciter output voltage at each speed, and consequently for each engine speed, a predetermined maximum generator output is available. As the generator load current rises, the corresponding increase in the decompounding series field ampere-turns reduces the generator voltage applied to the traction motors. This characteristic gives automatic overload protection to both generator and traction motors, whilst the motor voltage and current are adjusted to the speed and torque required.

LOW TENSION EXCITERS

Low tension exciters, normally working in parallel with a battery, are usually of the six-pole type, and are separately excited from the battery when running on open circuit, i.e. until closing of the reverse current charging cut-out switch, when battery, shunt field, and armature are connected in parallel. The constant voltage feature over the engine speed range is accomplished by the control system, which provides a reduction in exciter shunt field current at various intermediate running speeds. Regulation of the exciter voltage between notches is covered by the battery charging current passing through a series decompounding field winding, or by a voltage regulator.

Exciters which are belt-driven from the engine or generator shaft are also variable in speed, the voltage being controlled in a similar manner. Speed is generally stepped up from the main driving shaft by means of the belt pulleys, this resulting in a smaller machine with a four-pole field system.

The output of an exciter or auxiliary generator should be sufficient to provide power for the control system, for battery

FIG. 148.—RUMANIAN 4,400 H.P. D E LOCOMOTIVE
(*Sulzer Bros and The Railway Gazette*)

charging and for driving such other apparatus as the compressor, exhauster, water circulating pump and fan motors.

TYPICAL DIESEL-ELECTRIC UNITS

The following are some typical examples of diesel-electric units designed for various types of railway service, these having been selected to cover as wide a range as possible.

PASSENGER LOCOMOTIVE

The locomotive illustrated in Fig. 148 is one built in 1938 for the Rumanian railways to haul trains weighing 600 tons over long and steep gradients without assistance. It consists of two units coupled together, each containing an engine of 2,200 h.p. The wheel arrangement is of the $2\text{-}D_0\text{-}1 + 1\text{-}D_0\text{-}2$ type, each of the eight driving axles being powered by a separate traction motor. In working order the locomotive weighs 230 tons, and its peak tractive effort is 81,500 lb., which is sufficient to start a 600 ton train on a curved track with a rising gradient of 1 in 40.

Each half-locomotive is divided into a driving cab, a generator compartment and an engine room, a passage-way being provided down each side of the engine. In order to facilitate the removal of the engine generator unit, the whole central roof over the engine room is removable.

ENGINES

Each of the two Sulzer engines has twelve cylinders in two vertical banks of six, each bank having its own crankshaft and driving the main generator through a step-up gear of the spur type. Four running speeds are obtainable by governor control, 380, 485, 625 and 700 r.p.m. with respective maximum outputs of 700, 1,300, 1,900 and 2,200 brake h.p., the exhaust gas turbine supercharger being in operation in each case. A cross section of the engine is shown in Fig. 150 the dimensions given being in millimetres. The engine crank case and generator rest on two independent longitudinal beams, the whole being carried on the locomotive framework as one complete unit. This ensures rigidity between the engine and generator, and protects against damage due to distortion of the main frames.

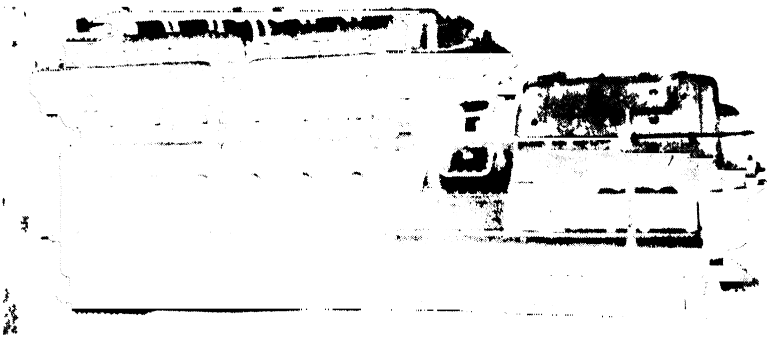


FIG. 149.—2,200 B.H.P. SULZER 12-CYLINDER FOUR-STROKE ENGINE
(*Sulzer Bros. and The Railway Gazette*)

Engine cooling is accomplished by means of a water system circulated by electrically-driven pumps, mounted, together with water-tanks, at the inner end of each half-locomotive. Above these are the radiators, air being drawn in at the sides of the locomotive, passed through the radiators, and finally expelled through the roof by motor-driven fans supplied from the auxiliary generator.

GENERATORS

The 1,250 kilowatt generators, which are of Brown-Boveri manufacture, follow the principles outlined under the heading

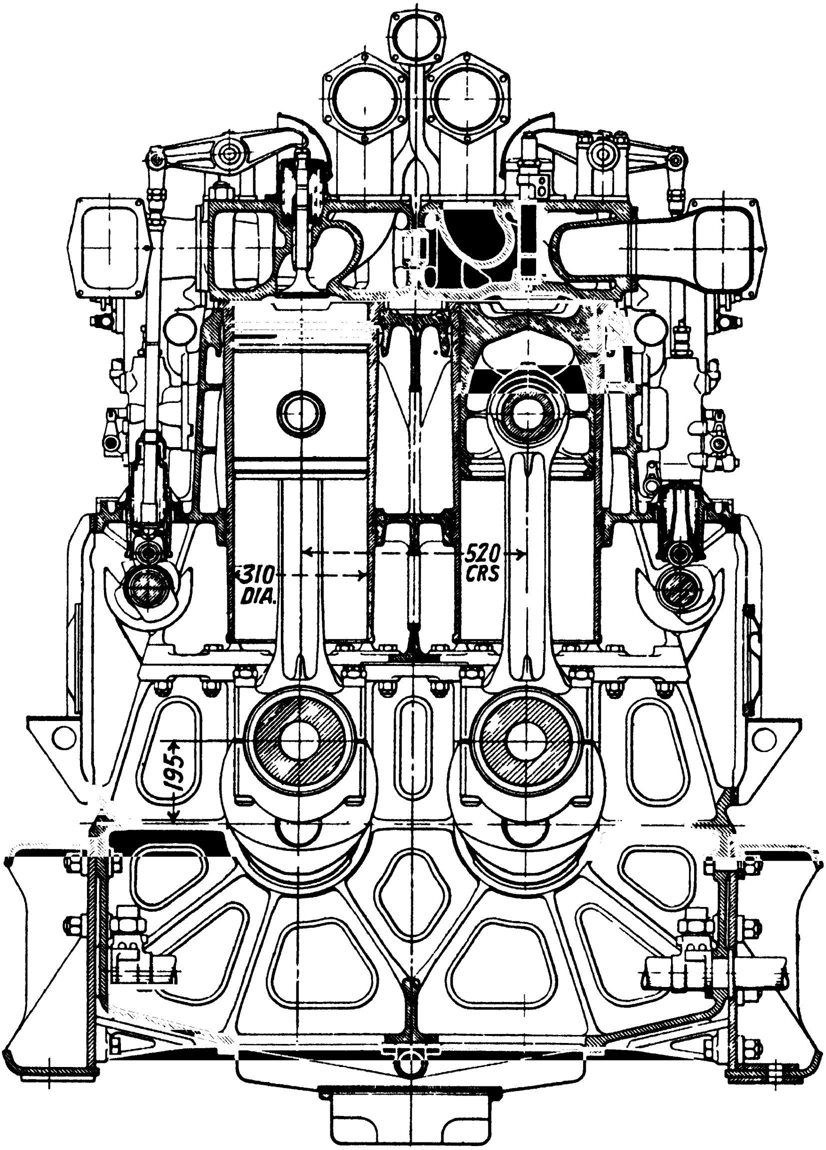


FIG. 150.—CROSS-SECTION OF SULZER 2,200 H P ENGINE

(Sulzer Bros and The Railway Gazette)

engine-driven generators (page 196). In this case the commutator is fitted nearest the engine, and the auxiliary generator mounted almost entirely within the main generator at the opposite end. Cooling is obtained by means of a fan at the driving gear end, which draws air through the auxiliary and main generators, over the commutator and finally expels it through the floor, a system which keeps any carbon dust from the brushes away from the windings.

TRACTION MOTORS

The traction motors, each of 390 h.p. are of the single armature type horizontally located as with nose-suspended types. Actually they are rigidly attached to the locomotive frame and drive the wheels through a hollow quill individual axle drive of the spring cup type, the hollow shaft being gear-driven from the armature with a reduction of 16 to 89. Fig. 152 shows the complete motor and driving axle assembly.

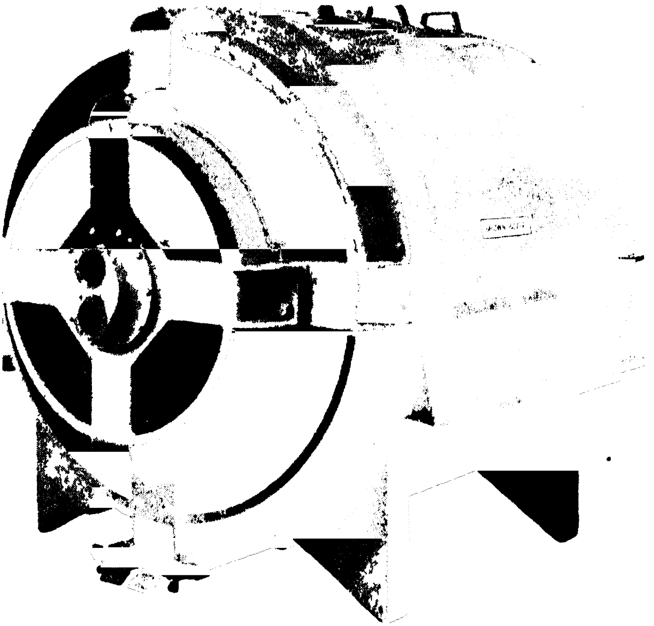


FIG. 151.—MAIN AND AUXILIARY GENFRATORS
(*Sulzer Bros. and The Railway Gazette*)

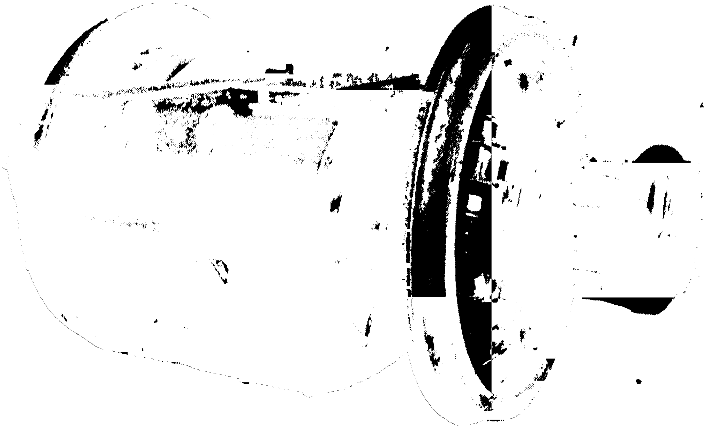


FIG. 152.—TRACTION MOTOR WITH QUILL AND CUP DRIVE
(*Sulzer Bros. and The Railway Gazette*)

Control of the locomotive is from the outer end of each unit, the driver having eight running notches to choose from. On the first four, a fixed engine speed and generator field current are provided, the horse-power developed varying with the load; whilst on the last four notches with a set engine speed, a definite horse-power is developed by variation of the generator field using a "servo field regulator" operated from the engine governor.

POWER CIRCUITS

Fig. 153 shows the power circuits for one half-locomotive. When the whole equipment is at rest, *BPC* the battery paralleling contactor is closed, so paralleling the batteries of each half-locomotive in preparation for starting the engines. On moving the starting handle, the appropriate engine starting contactor *SC* closes, and the generator, functioning as a series motor fed from the battery, starts up the engine. By a system of interlocking it is impossible to start both engines at once, or to connect the auxiliary generator to the battery when starting the second engine. Once both engines are running, *BPC* opens and isolates the two batteries. The battery is charged through a reverse current cut-out from the 70-kilowatt auxiliary generator at 250 volts, this voltage being maintained within close limits by a voltage regulator, which inserts resistance in the self-excited field circuit as the engine speed is increased. To move the locomotive, the reverse cylinder is first set to the desired direction, this operating the reverser in the usual manner. The controller handle is then moved from the "off" position to any running notch, thereby closing the main motor contactors *M*, and applying a field current to the main generator. The locomotive then moves away, its acceleration, speed and developed horse-power depending on the controller setting. When operating on notches 5 to 8 the servo field regulator comes into operation, its principle being as follows. The engine is set to develop a certain horse-power, and if this tends to increase or decrease it is immediately detected by the governor which operates a small piston valve controlling the oil admission to each side of a rotary piston. By this means the governor is able to operate a regulator connected to the rotary piston, and so vary the resistance in series with the separately excited field of the generator, thereby modifying the demand on the engine in such a way as to keep the horse-power output constant.

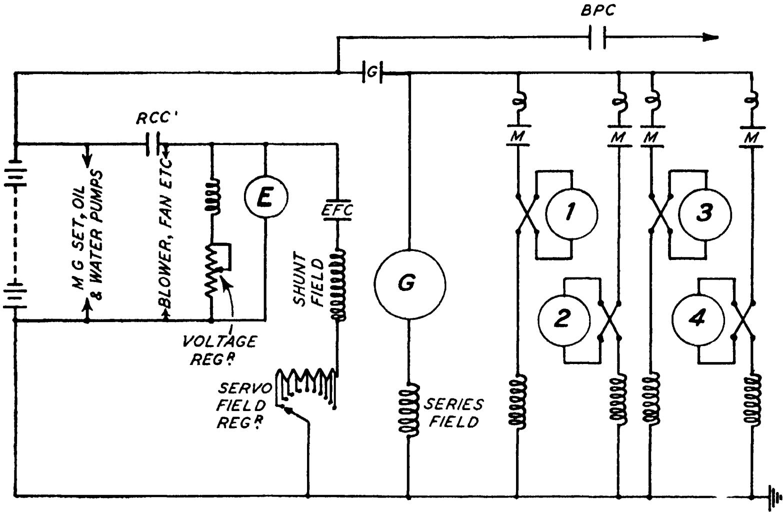


FIG. 153.—RUMANIAN LOCOMOTIVE POWER CIRCUITS

SHUNTING LOCOMOTIVES

The main advantages claimed for diesel-electric shunting locomotives are:—

(*a*) Available for service 6½ days weekly for 24 hours per day; it is estimated that 12 locomotives of this type can do the work of 19 steam locomotives.

(*b*) Full power output is immediately available on demand with a negligible fuel consumption when not actually working.

(*c*) A very high tractive effort can be made available at starting.

(*d*) Considerable reduction in operating costs as only one man is required per locomotive instead of two.

(*e*) Maximum comfort is provided for the driver with ease of control, as once the engine is running only two levers are used, one to control the speed of working and the other the direction of motion, rapid reversal being possible by movement of a small lever. Dual driving positions are fitted so that the driver may control the locomotive from either side, the usual "dead man" protection being fitted in the form of a pedal with a time lag of a few seconds to enable the driver to move from one side of the cab to the other without the tripping mechanism operating.

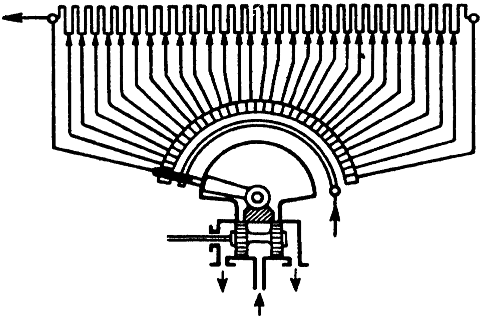


FIG. 154.—SERVO FIELD REGULATOR
(*Sulzer Bros. and The Railway Gazette*)

The locomotives shown in Figs. 155 and 156 are two versions of the locomotive which is now extensively used for diesel-electric shunting work in this country. It has appeared in the last few years in the above two forms, one of which has a single frame-mounted motor driving a jackshaft through a double reduction gear, the jackshaft being connected to the main driving wheels. Fixed engine speeds are employed, output being governed on the maximum speed by the "torque control" method.

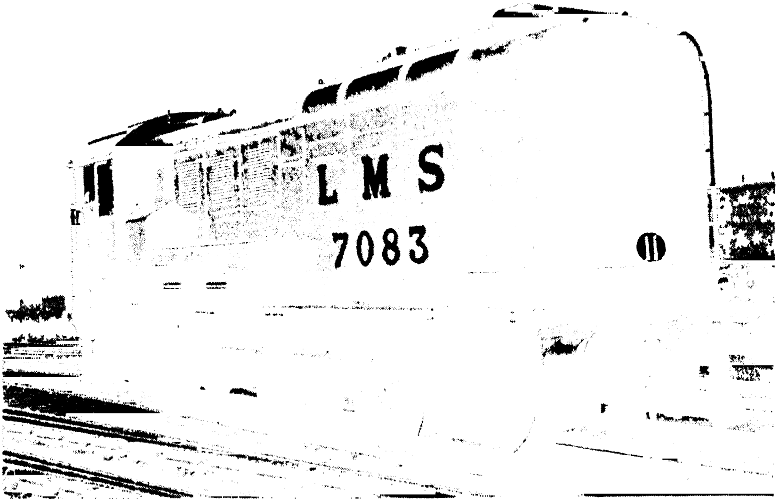


FIG. 155.—JACKSHAFT-DRIVEN SHUNTING LOCOMOTIVE

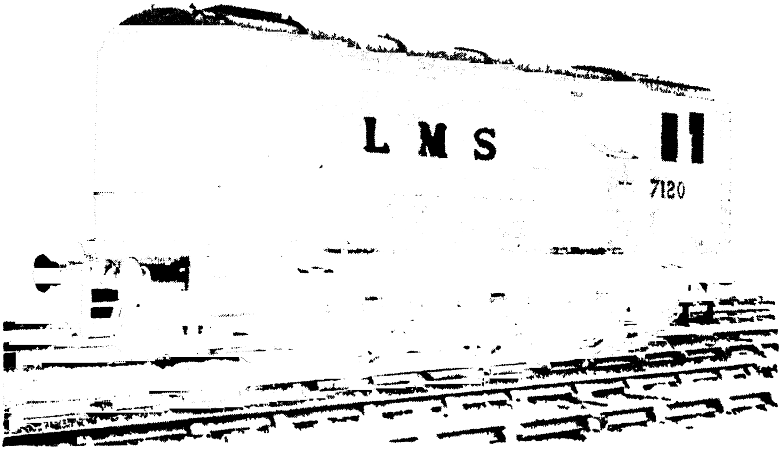


FIG. 156.—AXLE-HUNG MOTOR TYPE SHUNTING LOCOMOTIVE

(*English Electric—L.M.S. Railway*)

The second type has two axle-mounted motors connected in parallel, driving the leading and trailing axles through double reduction gearing. The engine speed is continuously variable from 300 to 680 r.p.m., output being governed throughout by the inherent characteristic of the generator.

The approximate weight of the locomotive in working order with sufficient fuel for two weeks operation is 50 tons. This is distributed between the three coupled driving axles, the wheel arrangement being 0–6–0, the standard for most British shunting locomotives. The haulage capacity is 800 tons at 10 m.p.h. on a level track, the maximum starting tractive effort being 32,000 lbs.

POWER UNIT

Power is supplied by a six cylinder 350-h.p. English Electric engine driving a 230-kilowatt generator, the armature of which has only one bearing, the inner end being direct coupled to the engine crankshaft while the frame is mounted on extensions of the engine crankcase. The whole unit is carried on three bearers, one at the front and two at the generator end, this being done in order to avoid any distortion due to flexing of the locomotive frames.

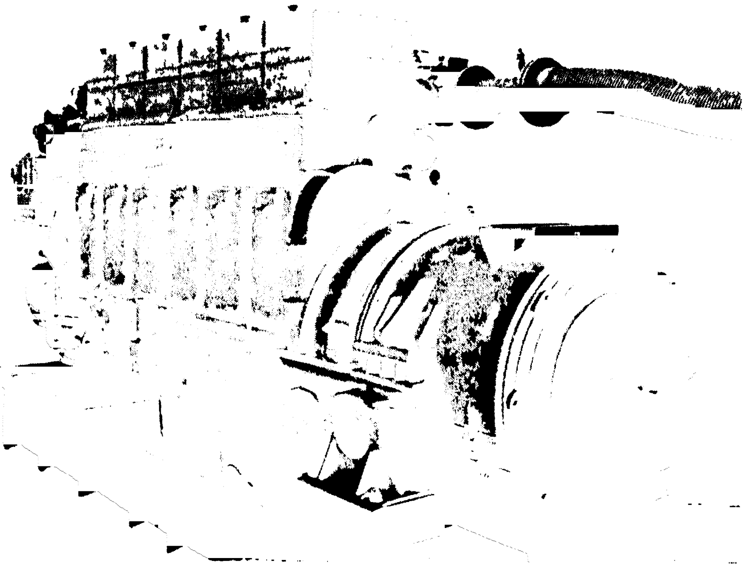


FIG. 157.—350-H.P. ENGINE GENERATOR SET

(*English Electric*)

The radiator and fan, which is belt-driven from the engine, are mounted at the leading end of the locomotive, and the engine and generator are then mounted between the radiator and driving cab at the rear. On the top of the generator are situated the compressor and the exciter-blower unit, both belt-driven from a pulley on an extension of the generator shaft (Fig. 158). Fixed to the rear bulkhead of the engine generator compartment are the field resistance units, used to control the generator and exciter excitation.

FIG. 158.—EXCITER BLOWER AND COMPRESSOR DRIVE

(English Electric)

The generator is cooled by a fan mounted at the engine end, which draws air over the commutator and through the windings, in this case the commutator being at the outer end of the armature.

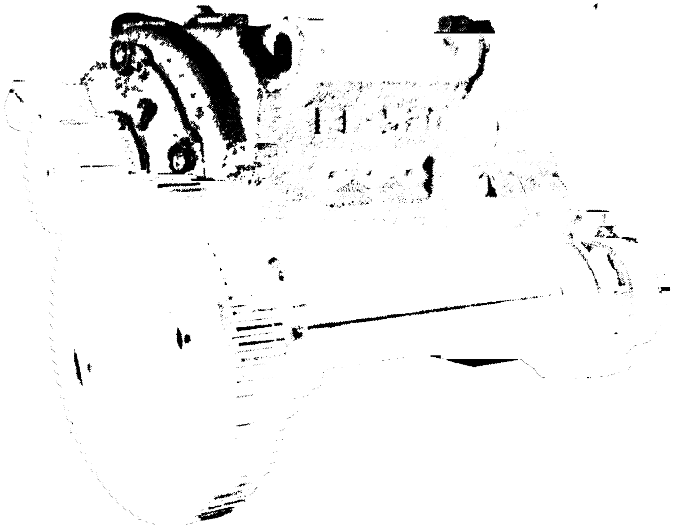


FIG. 159a.—318-H.P. MOTOR

(*English Electric*)

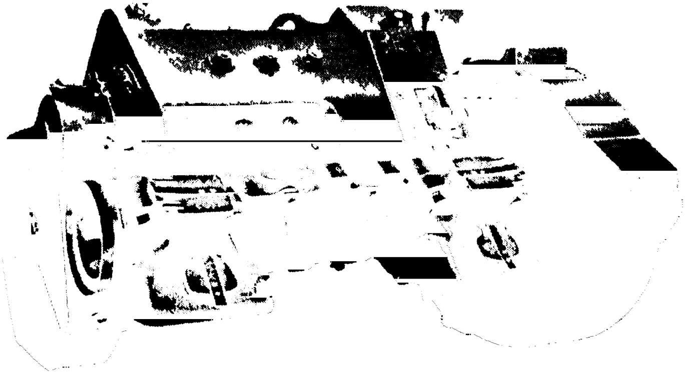


FIG. 159b.—135-H.P. MOTOR

(*English Electric*)

EXCITER-BLOWER UNIT

The exciter-blower unit consists of an 85-volt 6-kilowatt auxiliary generator, with its commutator at the pulley end, and a blower fan on a shaft extension at the other end of the armature, which delivers 2,000 cu. ft. of air per minute to the traction motors at maximum engine speed.

TRACTION MOTORS

Two types of traction motor are shown in Fig. 159. In the jackshaft-driven locomotive the motor, which has an output of 318 h.p. on its one hour rating, is mounted between the generator and the rear bulkhead, and drives the jackshaft situated below it through double-reduction gears. In the second type the two 135-h.p. one-hour-rated motors drive the leading and trailing axles also through double-reduction gearing. A special feature of this drive is that the intermediate shaft may be moved so that the gears disengage, so enabling the locomotive to be towed without turning the traction motors. This is necessary as the maximum safe speed is 20 m.p.h., a value which may easily be exceeded when the locomotive is being towed from depot to depot.

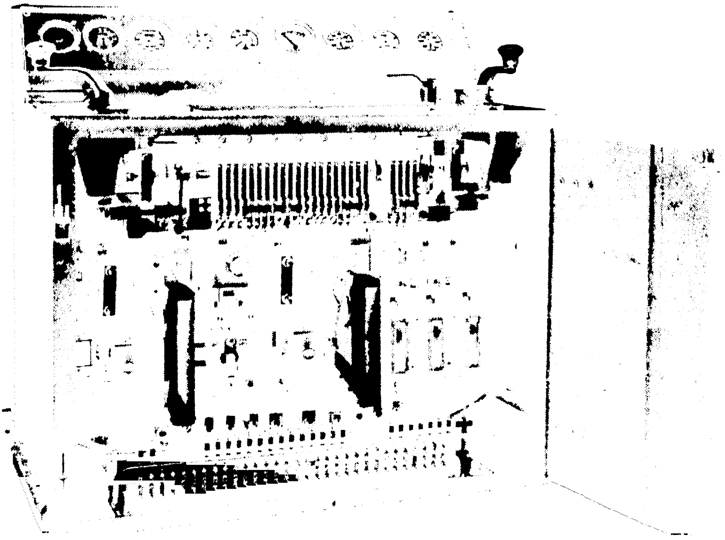


FIG. 160.—CONTROLLER DESK

(*English Electric*)

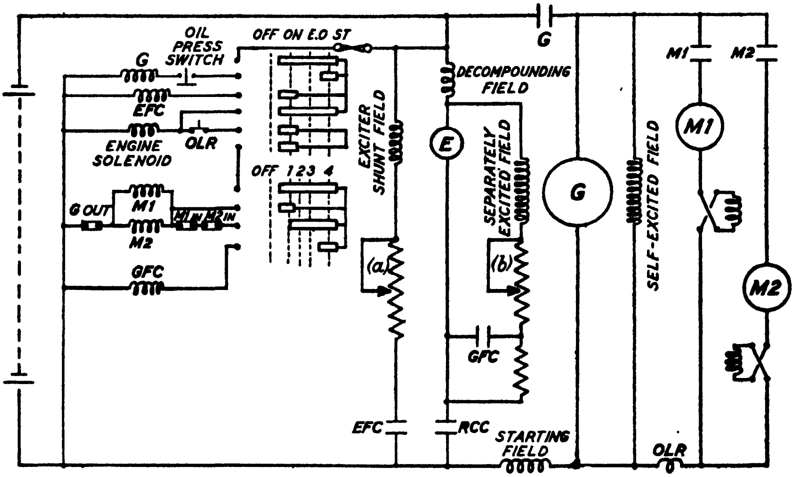


FIG. 161.—CONTINUOUS SPEED CONTROL SCHEME
Resistance (*a*) is inserted as engine speed increases
Resistance (*b*) is cut-out progressively from notches 1 to 2

The control gear is housed in a desk fitted in the driving cab (Fig. 160). This desk contains the master controller, reverser, main power contactors, overload and earth fault relays, etc. Three control handles are fitted, the master switch with a detachable key in the "off" position, and the main and reverse cylinder handles which are duplicated at each end of the desk. To start the engine, the master switch is moved to the "start" position, which energises the engine governor control valve and closes the starting contactor *G.*, thereby motoring the generator from the battery. After the engine fires, the master switch is allowed to return to the "engine only" position, where, by moving the main cylinder control handle over the speed range, the engine may be accelerated on no load up to its maximum speed for checking purposes. As mentioned previously the two-motor locomotive is fitted with continuous speed control and the jackshaft-driven type with fixed speed control, the actual control schemes employed only differing in minor detail from the simplified schemes described in the following.

CONTINUOUS SPEED CONTROL

In continuous speed control (Fig. 161), the traverse of the master controller cylinder is divided into four sections.

(*a*) Notch 1 closes the motor contactors and applies minimum battery field current to the generator with the engine running at 300 r.p.m.

(*b*) From notch 1 to notch 2 several running positions exist, on each of which the battery field current is increased, the engine speed remaining constant throughout at 300 r.p.m.

(*c*) From notch 2 to notch 3 the battery field current is maintained at a constant value, while the engine speed is increased uniformly to 680 r.p.m. by means of a cam, mounted on the master controller cylinder, which adjusts the engine governor setting through a system of rods and levers.

(*d*) At notch 3 the engine is at full speed and, to obtain further power, the handle is moved to notch 4 which doubles the value of the battery field current, thus bringing the generator to its maximum output characteristic.

By this method, a series of running positions is obtained during which the voltage applied to the traction motors is raised from zero to a maximum without the use of starting resistances or of series-parallel operation. In order to maintain the exciter voltage, and hence the generator battery field current, at a constant value with increasing engine speed between notches 2 and 3, a series of fingers are fitted on the master controller cylinder which reduce the exciter field current by the insertion of resistance steps into its field circuit as the engine speed increases.

FIXED SPEED CONTROL

This control uses four fixed engine speeds and various generator battery field current values to form a combination of ten running notches, on the last of which "torque control" is employed. Referring to Fig. 162, on moving the master switch to the "on" position the exciter self-field circuit is completed by the closing of *EFC* contactor. In consequence, the exciter builds up and applies minimum battery field current to the generator, which therefore builds up to its corresponding characteristic.

To move the locomotive the reverse handle is set, and the control handle moved to notch 1; this closes the motor contactor *M*, and supplies current from the generator to the traction motor. Notches 2, 3 and 4 each increase the generator battery field current, the engine speed being retained throughout at its minimum of 350 r.p.m. On moving to notch 5 the engine speed is increased to 460 r.p.m., while the battery field current is reduced in value. Notch 6 returns this field current to its previous

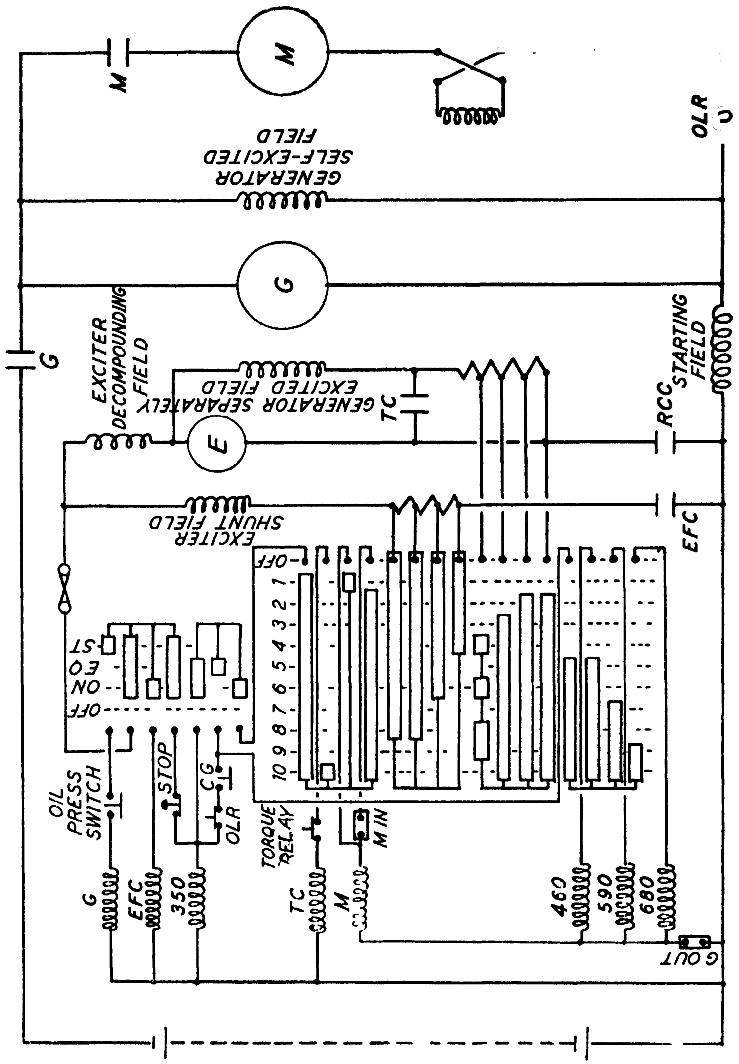


FIG. 162 —FIXED SPEED CONTROL SCHEME (SIMPLIFIED)

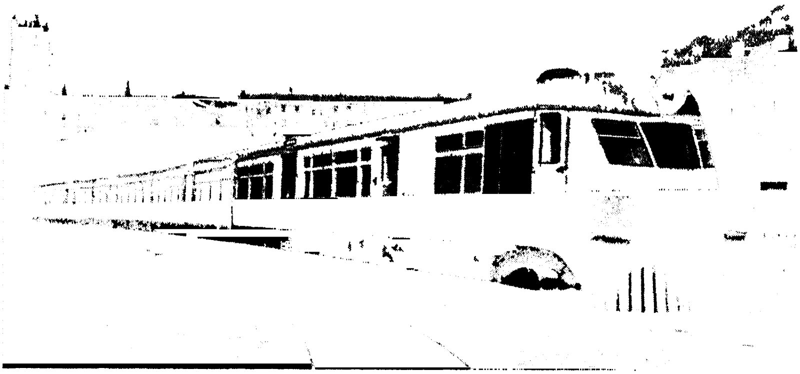


FIG. 163.—MULTIPLE-UNIT DIESEL-ELECTRIC TRAIN

(*English Electric*)

maximum value, while notches 7 and 8 repeat this process with an engine speed of 590 r.p.m. The maximum engine speed of 680 r.p.m. is obtained on notch 9, and finally, on notch 10, a further increase is made in the battery field current, and at the same time torque control is brought into operation.

Any attempt to overload the engine when operating on notch 10 is detected by the torque control relay, which is connected to the engine governor, and automatically reduces the generator voltage, and hence its output, in the event of overload. This is accomplished by a reduction of the battery field current through the medium of the contactor *TC*, which inserts a certain amount of resistance. In operation, when the engine is developing its full power, this contactor opens and closes rapidly, its speed of vibration depending on the main generator current.

As previously, the exciter voltage is maintained constant over the engine speed range by insertion of resistance into its field circuit with each increase in speed.

All contactors and relays for both systems of control are of the electro-magnetic type, operated from an 85-volt battery which is also used for lighting, and for illumination of the instrument panel mounted at the back of the desk. The most arduous duty however, which the battery is called upon to perform, is that of starting the engine, which it may be required to do several times daily. In consequence the battery must be continually on charge to maintain its condition, this being accomplished by charging from the exciter through a reverse current relay, i.e. one which only allows current to flow in the charging direction. Stability is obtained by the decompounding series field winding of the exciter.

FIG. 164.—DRIVING CAB OF MULTIPLE-UNIT DIESEL-ELECTRIC TRAIN

(*English Electric*)

MULTIPLE-UNIT STOCK

The trains described in this section were supplied to the Ceylon Government Railways in 1937 for operation of long distance suburban services. Each consists of four vehicles, two motor-coaches and two trailers. Articulated bogie construction is used throughout, there being one bogie between each motor-coach and its adjacent trailer, and one between the two trailers. The front end of each motor-coach is carried in the normal way on a driving bogie, on which are mounted two axle-hung traction motors, the main engine-generator unit being situated above in the main frames. It is possible to operate two trains coupled together with all the engines and control gear operated from one master controller through a control train-line. Each unit is fed from this line through a multiple-way control cut-out switch, and in the event of a fault on one motor-coach, its equipment may be isolated by opening this switch, thus enabling the train to continue on its way.

Each motor-coach is divided into five sections as follows:—

Driver's cab at the front end.
Engine room.
Generator and control compartment.
Guard's and luggage compartment.
Passenger saloon.

The engine and generator room houses the main power unit, consisting of a six-cylinder engine of 200–220 h.p. driving a main generator with an overhung exciter. The radiator fan motor is mounted on the floor, the fan being belt-driven, and expelling air from the engine room through the radiator mounted in the coach side. In addition to the main generator field, the exciter supplies the exhauster motor and control gear, and charges the battery for lighting, etc.

Vacuum braking is used, exhausters of the two-speed type being mounted in each motor-coach, and controlled from the driver's brake valve. Dead man protection is fitted in duplicate on the master controller handle and as a pedal situated at the driver's feet, the holding down of either of which is effective in retaining normal operation.

ENGINE

The engine is of the high speed type, with running speeds of 580, 900, and 1,350 r.p.m., the governor setting being adjusted electrically from the master controller. Mounted on an extension of the engine crankcase is the generator, which has a continuous rated output of 120 kilowatts at 1,350 r.p.m., and is of series decompounded design as described earlier in this chapter. The exciter is of 57-volt 7-kilowatt output, its armature being carried on an extension of the generator shaft, and its frame bolted to the

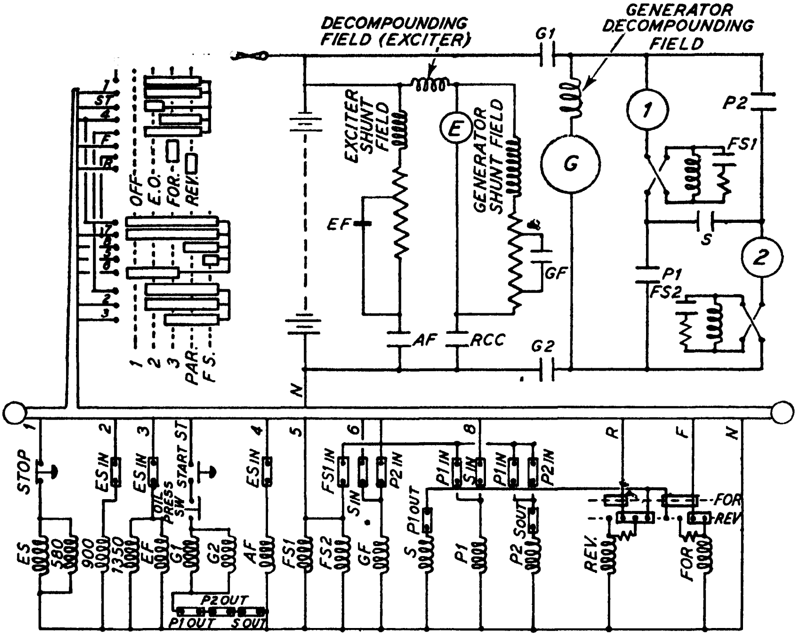


FIG. 165.—SIMPLIFIED CIRCUIT DIAGRAM—DIESEL-ELECTRIC MULTIPLE-UNIT MOTOR-COACH

main generator endplate. As with the shunting locomotive, the whole engine-generator unit is carried on three bearers to eliminate distortion.

TRACTION MOTORS AND CONTROL GEAR

The traction motors are axle-hung and nose-suspended with a single reduction drive as fitted in standard motor coach stock, the control being so arranged that they can be operated in series, in parallel, or with shunted fields.

Fig. 165 shows a simplified arrangement of the connections, the equipment being operated as follows. To start the engine, the master key is inserted on the controller and the reverser moved to the "engine only" position, after which pressure on the engine starting switch in the cab will start up the engine by closing contactors *G*1 and *G*2 thereby motoring the generator, from the battery. To move the train, the reverser is set to "forward" or "reverse", this completes the exciter field circuit, with consequent building up of the exciter volts and the generator shunt field. There are five running notches, the first three with the traction motors in series and engine speeds of 580, 900 and 1,350 r.p.m. respectively. Notch 4 changes the motor connections to parallel using shunt transition, a momentary reduction in generator field current, and hence main current, being made by the opening of contactor *GF*1, driving transition. The last notch applies shunting resistances to the traction motor fields. An interesting feature is that on notching back from notches 4 and 5, parallel and field shunt motor connections are maintained back to the first notch, and consequently can be used at reduced engine speeds.

RAILCARS

The diesel-electric railcar has been giving satisfactory service in several parts of the world for more than a quarter of a century. Units range from four-wheeled vehicles weighing 17 tons in use in Germany to eight-wheeled 63-ton cars in Canada. Engines are usually about 150 to 300 h.p. but certain railways are operating railcars with engines of 500 to 600 h.p. Maximum speeds vary from 40 to 100 m.p.h. according to the operating conditions and service required.

The electrical system of a railcar is very similar to that of the multiple-unit motor-coach described in the previous section except that no train-line connections are necessary. Modern design tends to simplify the electric transmission and control gear as much as possible, so as to compete favourably with the various systems of mechanical transmission available for such units.

From the above examples, it is clear that much of the equipment used for normal D.C. electric traction work is the same or very similar to that used in diesel-electric traction, hence the author's decision to include details of the various control schemes and apparatus used in applications of the latter principle.

Chapter 9

TESTING AND MAINTENANCE

Tests carried out on traction motors at the manufacturers' works are made with the twofold purpose of checking: (*a*) that the temperatures after running on rated loads, and also the characteristics, are within the permissible limits of guaranteed figures; (*b*) that the motors are mechanically sound after tests corresponding to the most severe conditions likely to be encountered in service. These include overloads, overvoltage, overspeed and insulation tests, where weaknesses or faults in windings, soldered winding joints, commutator, armature banding, insulation, balance and bearings may become apparent.

SERIES MOTOR TESTS

A simple and comprehensive test scheme in common use is that generally known as the "Series Hopkinson" back-to-back test method. The actual connections used between the testing equipment and motors under test are shown diagrammatically in Fig. 166.

Advantages of this method are:—

(1) Simplicity of circuit and few external connections.

(2) Adaptability, in which function and rotation of machines can be reversed easily by means of test stand switches, external connections remaining the same throughout.

(3) Easy control of load current and voltage.

(4) Power supply losses comparatively small.

(5) Useful method for testing very high voltage machines, as the voltage required on the series booster corresponds to the difference in voltage between the motoring and generating machines under test, i.e. 15 to 20 per cent of the motor voltage.

(6) As both motoring and generating machine armatures are in series and carrying the same current, the resulting temperatures at the end of a heat run are accepted as a test on both machines simultaneously, this being more economical from the point of view of production than individual testing.

Motor efficiency calculations based on the Series-Hopkinson test method are given as follows:—

$$L_m = (R_a + R_i + R_f)\, I_1^2 + C.$$

$$L_g = (R_a + R_i)\, I_1^2 + V_{gf}.\, I_2 + C.$$

$$L_m + L_g = \text{output of CB} + \text{EB}.$$

$$= (V_m - V_g)\, I_1 + V_{gf}.\, I_2 \ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$L_m - L_g = (R_a + R_i + R_f - R_a - R_i)\, I_1^2 + C - C\text{-}V_{gf}.\, I_2$$

$$= R_f.\, I_1^2 - V_{gf}.\, I_2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Adding (1) and (2). $2L_m = (V_m - V_g)\, I_1 + R_f.\, I_1^2.$

but $R_f.\, I_1^2 = V_{mf}.\, I_1.$

$$\text{Therefore } L_m = \frac{(V_m - V_g)\, I_1 - V_{mf}.\, I_1}{2}$$

$$\text{Efficiency of motor} = \frac{\dfrac{2V_m.\, I_1 - (V_m - V_g)\, I_1 + V_{mf}.\, I_1}{2}}{V_m\, I_1}$$

$$= \frac{V_m + V_g - V_{mf}}{2V_m} \times 100\%.$$

Symbols used are as below, and as in Fig. 166.

L_m Motor losses.
L_g Generator losses.
R_a Armature resistance.
R_i Interpole resistance.
R_f Field resistance.
C Core, windage and friction losses (assumed to be the same in both machines).

TEMPERATURE TESTS

For production testing of machines of standardised design a temperature test at the nominal short rating (usually one hour) is carried out on a pair of machines, the voltage and current of the motoring machine being held constant for the rated time, records of the speed and the various measurements, as indicated on the test scheme Fig. 166, being made at 15-minute intervals. On shut down, surface temperatures of the commutator, armature and field system are measured by thermometer, and at the same time, resistance measurements are made of all windings from which the actual copper temperatures are calculated. When testing forced-ventilated machines, a temporary ventilation system is set up in order to provide the necessary cooling air.

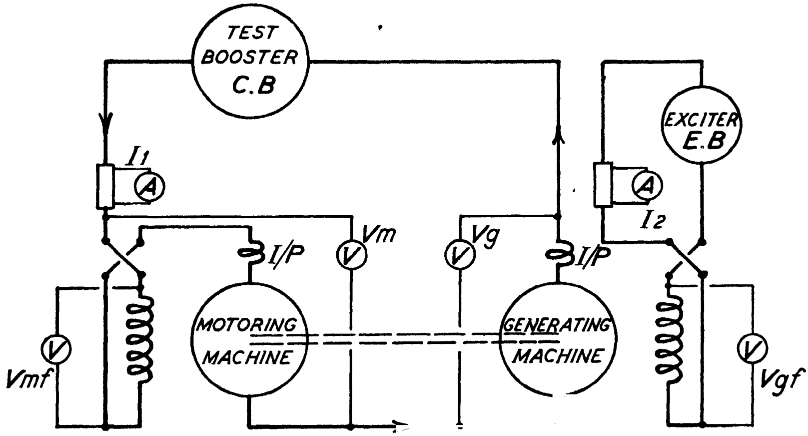


FIG. 166.—SERIES-HOPKINSON TEST CIRCUIT

SPEED-LOAD CHARACTERISTIC TESTS

In order to ensure reasonable load balance between motors on multiple-unit stock, and that accelerating currents and the running speeds are within desired limits on single-motor equipments, it is necessary to measure the speed-load characteristics of motors as a standard routine test, the usual tolerance of ± 2½% being allowed for variations in speed from the guaranteed values. The motor speed is recorded with the machine hot at the one hour rating figure, load currents ranging from 50 per cent above the normal rated value, down to a point corresponding to the maximum curve speed, these tests being made on all the tappings of tapped series field machines. On reversible machines, speed variation from clockwise to anti-clockwise rotation must not be more than 2 to 3 per cent.

COMMUTATION AT MOTOR BRUSHES

Commutation at the motor brushes is observed over the whole range of working loads, including such adverse conditions as over-voltage, overload and high speed on the weak field tapping. Permissible sparking is such as not to cause burning of commutator bars or the carbon brushes.

OVERSPEED

A maximum safe running speed is quoted for all rotating machines, usually about 20 per cent above the maximum working

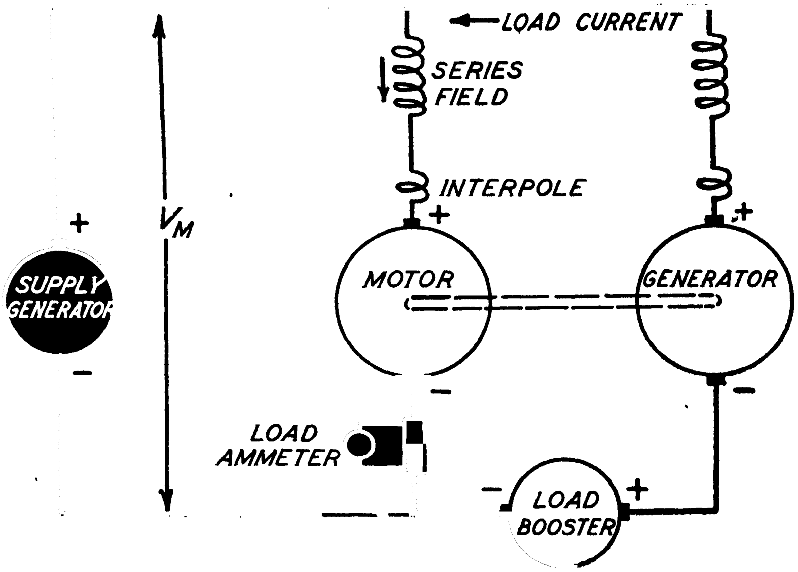


FIG. 167.—SERIES MOTOR TEST CIRCUIT

speed, so as to give a margin of safety between the latter and that corresponding to the ultimate mechanical strength of rotating parts when under centrifugal stress. During an overspeed test, particular attention is paid to ensure that no temporary or permanent "springing" of the commutator segments occurs, and also that bearings run smoothly. Balance of armatures should be such that vibration when running is reasonably small, and that any critical vibration amplitudes occurring in the speed range are insignificant.

HIGH-PRESSURE INSULATION TESTS

These tests are carried out in accordance with the "Electrical Standards Association" specification for traction machinery, and are made between all windings and the frame, and between independent sections of windings, such as shunt and series layers of composite field coils. Insulation resistance should be as high as possible, one megohm being the absolute minimum permissible.

Another test circuit as shown in Fig. 167 may be used for testing series motors. In this method, the two series motors under test are connected in parallel with the supply generator, a booster machine being interposed between the two under test and providing the means of load regulation.

This method is not very flexible for varying types, but is useful in tests on heavy-current machines where a large capacity booster is not available, only a low voltage corresponding to the back e.m.fs. of the machines under test being required from the load-regulating booster.

COMPOUND MOTORS

Testing of compound traction motors is somewhat more involved especially where regenerative characteristics are required. It may be found most convenient to test the machines individually, coupled to a permanent test machine for electrical loading. A typical separate loading test circuit is shown in Fig. 168, full range of loads from "motoring" to "generating" of the motor under test being obtained by regulating the field of, and the armature supply to, the loading machine. Trolley-bus motors are unidirectional in rotation, therefore slight deviation of the brush position from magnetic neutral is permissible where improvements in the commutation and the shape of speed-load characteristic curves can be obtained by such brush movement.

GENERATORS

Main generators for diesel-electric units which have drooping voltage-load characteristics, may be conveniently tested using the

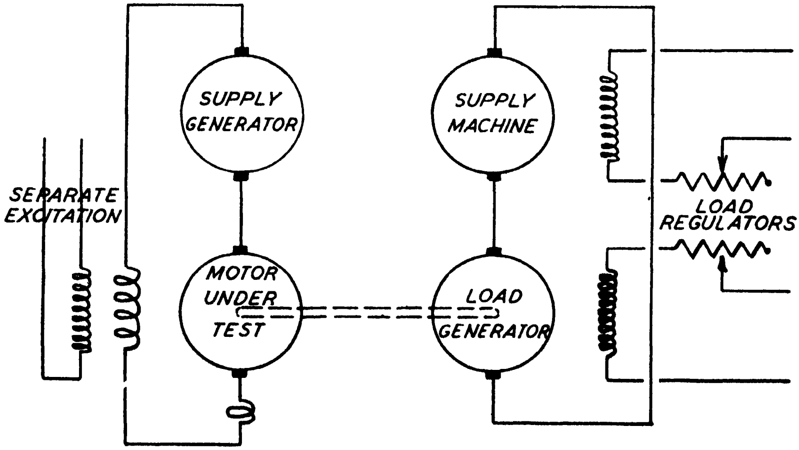


FIG. 168.—SEPARATE LOADING TEST CIRCUIT

"separate loading" method with a pair of generators coupled together, one machine acting as a motor during generating tests on the other. The armature supplies, being independent of one another with this test method, enable the voltage of the motoring machine to be raised relative to that of the generating machine, so as to provide the combined efficiency losses without increasing the motor current above that of the generator, thus preventing excess winding temperatures; heating being proportional to the square of the current. Standard tests similar to those as described for traction motors are made, including the extreme conditions of load, speed, voltage, etc.

AUXILIARY EQUIPMENT

This equipment is subject to the usual routine tests, such machines as motor-generator sets and exciters being tested individually, and the output energy dissipated in resistance grids. This power being of a low order does not represent much loss, and the method facilitates load regulation. Compressor, exhauster and blower motors, generally of the series motor type, may be tested back to back in pairs using the Series-Hopkinson method as described for traction motors.

DEVELOPMENT TESTING

Development testing and testing of prototype machines is more comprehensive than that for production purposes, and is carried out in precise detail as follows.

(*a*) Cold resistance of all windings, these are checked against the calculated values, ensuring correct material has been used in construction, and also used as the basis for temperature calculations.

(*b*) Field magnetisation curves, taken to check the

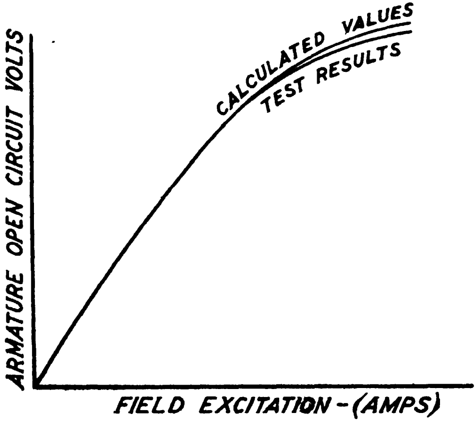


FIG. 169.—VOLTS-EXCITATION CURVE, SHOWING DEVIATION FROM DESIGN VALUES

effective air gap between armature core and poles, and also that the material and magnetic section of the frame is correct to drawing. It is not possible to pre-estimate exactly flux density in a magnetic circuit of cast metal, due to the slight variations in thickness and permeability. The usual method of measuring saturation curves is to drive the machine armature at constant speed by external means, with the main field coils connected to a variable current supply. Readings of open circuit armature voltage are taken for field currents from zero up to a value approaching flux saturation. Generated volts are directly proportional to flux entering the armature, therefore open circuit volts are equal to the flux per pole multiplied by a constant. A curve as illustrated in Fig. 169, may be plotted, from which any deviation from the design estimate is indicated and may be rectified.

(*c*) Temperature test at the nominal one hour rating, recording resistances, inlet and outlet air temperatures, internal circulating air if possible when the machine is of the totally enclosed type, surface temperatures of frame and bearings, at short intervals. Finally on shutting down, the hot armature resistance with a cooling curve and internal surface temperatures by thermometer are taken. By plotting the armature resistance cooling readings and producing the curve to zero time, the exact winding temperature at the instant before shutting down can be calculated. From the various data obtained, the effectiveness of ventilation and heat dissipation may be checked. Permissible one hour rating temperature rises according to traction standards are 120° C., by resistance and 90°C. by thermometer.

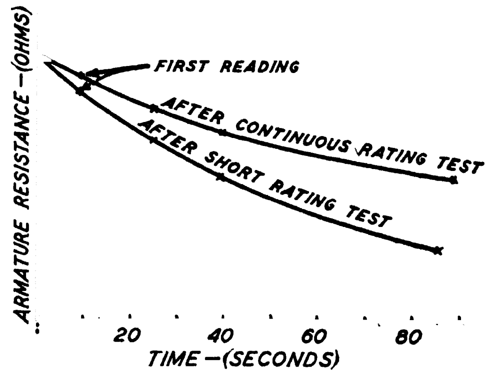


FIG. 170.—USE OF COOLING CURVES TO FIND TRUE HOT RESISTANCE

(*d*) A continuous rating temperature test is usually made immediately following the one hour test, and continued until such a time that the machine has reached a final steady temperature. This test may take up to six or eight hours on large machines. On shut down being made, readings are taken as described for the one hour test. Permissible temperature rises in this case are 105° C. by resistance and 75° C. by thermometer. It may be found that these temperature limits have not been reached with the nominal rating figures, and it is useful for data recording purposes, to carry on the test at a slightly increased rating, finally obtaining the maximum rating value for the particular type of machine.

The use of resistance cooling curves is shown in Fig. 170.

(*e*) Speed-load characteristic tests are taken to ascertain the actual machine characteristics, which should lie close to the designed curve figures in order that the tractive efforts and speeds for motoring currents shall be within specified limits. It is necessary on reversible motors that brushes are in the electrical neutral position, in order to eliminate speed variation in the two directions of rotation. Due to constructional tolerances, the mechanical neutral may vary slightly from the electrical neutral position as indicated by the motor speeds, in which case adjustments are made after the initial tests. Where possible it is desirable to couple motors through their particular type of gearing or special drive as used in service, in order that the gear efficiency and also the mechanical endurance of gears and bearings may be checked.

(*f*) Efficiency and separate losses. Working efficiencies may be closely approximated during load tests either as described earlier in this chapter for series motors or by taking the square root of the overall fractional efficiency of a pair of machines loaded back to back. These methods assume the similarity of machine efficiencies and in the latter case neglect any losses incurred in the mechanical drive between machines. In order to calculate the exact efficiency and to check that the various losses are normal, it is necessary to measure each source of loss separately. Heating or copper loss is obtained directly from the product of the current squared and resistance. Armature core eddy current loss may be measured over the speed and field excitation range, by either driving the machine under test with a separate motor (with predetermined speed-input curve), or by running the test machine as a separately excited motor and measuring the input power to the armature. The actual eddy current loss values may then be obtained by interpolation after plotting curves of total input as shown in Fig. 171.

COMMUTATION

The introduction of better insulating materials and constructional methods, together with the demand for higher-powered units with flexibility of application, have forced the rating of main traction motors towards their maximum. This trend of events has resulted in good commutating characteristics of machines being more difficult to achieve. Sparkless commutation of course is the ideal condition and is usually achieved over the normal load range, allowance being made for slight sparking at the brushes under extreme tests. With this in mind, tests are made by temporarily varying the interpole field strength whilst commutation is observed and noted, the purpose of such a test being to ensure that under normal conditions, good commutation is obtained when working at the

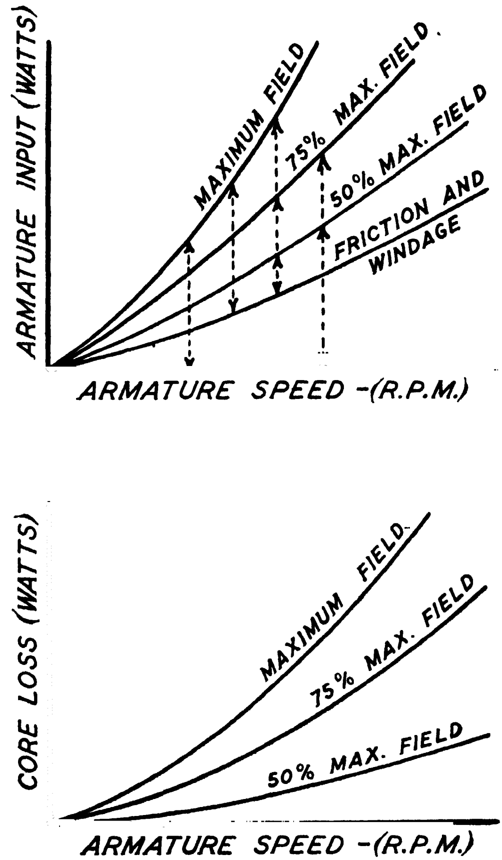


FIG. 171.—TYPICAL LOSS CURVES

average point of interpole flux range, so as to provide a margin for under- and over-commutation at light and heavy load values respectively.

STANDARD CONTROL GEAR TESTS

Normal practice in the design of remote operated control-gear is to ensure operation of contactors and relays at less than 50 per cent of the normal operating voltage. This gives a margin for efficient operation under conditions corresponding to a low state of battery charge, or low line volts in the case of line operated gear, with coil resistances equivalent to those at continuous rating temperatures. Individual testing of components is carried out to specifications set out on these lines.

CONTACTOR	*TYPE*	*FORM*..........
Assembly Drawing No.	....	
Operating Coil ..	Continuous Rating Minimum Operation .. .. Resistance	250 volts 116 volts 824 ohms.
Blowout Coil ..	Continuous Rating Check blowout at Coil turns ..	300 amps. 100 amps. 9
Main Contacts ..	Contact Gap .. Contact Pressure (closed)	$\frac{3}{4}$ in. ± $\frac{1}{16}$ in. 13 to 15 lb.
Auxiliary Contacts	Minimum Gap .. Wipe	$\frac{1}{8}$ in. $\frac{1}{16}$ in.
High Pressure Insulation Test at		2500 volts A.C.
Insulation Resistance to be not less than 100 megohms		

FIG. 172.—CONTACTOR TEST SPECIFICATION.

CONTACTORS

A typical test specification for a power contactor of the magnetic operated type is given in Fig. 172. The maximum arc rupturing capacity of a contactor is usually in the order of four or five times the normal rated valve, critical blowout being at low inductive currents. For this reason blowout check of standardised contactors is made at low currents, one third the continuous current value being specified in the example in Fig. 172.

RELAYS

(*a*) *Current limit relays.* The correct value of motor accelerating current and therefore tractive effort, is dependent on the operation of this relay on automatic control systems. Testing consists of the setting of pick-up and drop-off current values to specification, and ensuring efficient working of mechanical parts which may give rise to inconsistency of operation.

(*b*) *Overload relays.* Protection of electrical equipment against damage by sudden or sustained overload currents is provided in the operation of the overload relay. It is usual for these relays to be fitted with means of adjustment, the range of current tripping values being indicated on a calibration plate by means of a small pointer. Calibration is made on test by passing the appropriate value of current through the operating coil turns, adjusting the relay to trip when the current is applied suddenly.

All relays are calibrated similarly on test to the minimum operating condition, the actual settings being determined by the application, and final adjustments being made at site if necessary.

After complete assembly of the component apparatus in the control cubicles or grouped panels, all wiring is checked, timing of electrical interlocks set, and sequence of operation checked.

With electro-pneumatically operated control systems it is necessary to check all air piping for leakage at the various union joints, and that the magnet valves operate satisfactorily at maximum and minimum air pressures and voltages.

DESIGN TESTING

In the design of control gear the following points govern the size and type of equipment. All power circuit parts must be capable of carrying full load current continuously, without exceeding a temperature rise of 60 to 75° .C. Contactors must be capable of rupturing currents much in excess of those encountered in normal service, to ensure some protection when faults develop in the system. All operating coils on magnetic or electro-pneumatic moving systems must be capable of operation under extreme conditions of pressure and voltage, and of withstanding continuous energising without excessive temperature rise.

When a new piece of control apparatus has been designed, an experimental model is constructed and subjected to short and continuous rating temperature tests, operation figures are then taken hot and cold, and special flux and arc rupture tests carried out on contactors. Finally the apparatus is put on an endurance test and may do anything from 200,000 to 1,000,000 operations. Only when the designer is satisfied with its electrical and mechanical soundness is the piece of equipment put into production.

COMBINED TESTS

On the completion of the first equipment on any traction contract, it is usual to carry out combined tests on the whole equipment where new schemes or apparatus types are involved. The gear is arranged on stands and connected up as in the locomotive or motor-coach, traction motors being coupled to resistance loaded generators in order to obtain normal line currents. Sequence testing of the control-gear is carried out first in detail, and providing this is satisfactory, the power circuits are connected to an appropriate supply and acceleration tests made which are comparable with those obtained in service. It is frequently found that slight adjustments or alterations are necessary and these tests enable such rectifications to be carried out during manufacturing instead of having to make modifications on site and in service.

SITE TESTING

When the locomotive, train or tramcar has been erected, a series of tests are carried out to check the electrical operation and the mechanical soundness. The wiring and power cabling is thoroughly checked and its insulation resistance to earth measured. The control gear is then operated from an independent supply, all contactors, relays, etc., being tested out and the notching sequence verified to the schematic operation diagram. If all this is satisfactory, the main high tension supply is connected on and the various auxiliary equipment tried out. The vehicle is then moved slowly under its own power and finally taken out for track tests.

TRACK TESTS

The following tests are outlined for an electric locomotive, but a similar series may be carried out on any electrically propelled vehicle. In addition certain of these tests are only conducted on one or two locomotives of a series.

(*a*) Operation tests consisting of tests over the speed range on varying loads.

(*b*) Acceleration and braking tests running light and with trains of varying weight.

(*c*) Power consumption tests.

(*d*) Special tests on low and high line voltages etc.

To enable continuous records of the various currents, voltages, speeds, etc. to be made, two methods may be employed. First is the "traction recorder", consisting of an electro-speedometer, main ammeter and voltmeter operating "stylus" pens on moving paper charts, this being most suitable when tests over a period of time are required. Secondly comes the "Cathode ray" oscillograph which may be used for any number of measurable quantities depending on the number of tubes employed. The results are photographed on a continuously moving paper film and instantaneous phenomena can be easily analysed.

SERVICE MAINTENANCE OF ELECTRICAL EQUIPMENT

Systematic inspection and cleaning of electrical apparatus is of the utmost importance, and failure to carry out this work periodically may result in improper operation or breakdown of a more or less serious nature. Maintenance is usually split up into three classes as follows:—

(*a*) Light or shed inspection. This may be made perhaps every ten days; inspection of the main motor brush-gear and commutator, contacts of power contactors and overall insulation resistance being carried out. Any sign of excess heating is noted, and followed by investigation as to the cause. Oil reservoirs of axle and motor armature bearings (if of the sleeve type) are recharged.

(*b*) Heavy inspection, made at periods from three to six months depending on the climatic and service conditions. A similar general inspection is made of all equipment, but in addition thorough cleaning of external insulation, adjustments to bedding of contacts, renewal of contact tips where necessary, replacement of worn motor brushes and recharging of bearing lubrication including grease lubricated types is carried out.

(*c*) General overhaul, usually made annually and covering removal and stripping for internal inspection of rotating machines, and renovation of control apparatus. All electrical and mechanical parts on which wear is likely to occur should be examined and lubricated as necessary. Cables should be examined to ensure that no chafing is taking place and that all cleating is effective.

On new equipment, attention should be paid both electrically and mechanically during the first few months in service, this serving as the "running in" period when the various working parts are settling down and acquiring their correct working positions and surfaces.

With diesel-electric equipment, the diesel engine should be subject to frequent attention, light inspection weekly and monthly and heavy inspection every 1,000 hours running. Complete dismantle and overhaul at periods of up to two years is possible with the slower speed type of engines.

Chapter 10

METADYNE TRACTION EQUIPMENT

In and around large cities, especially where traffic requirements are increasing, thereby calling for higher schedule speeds, increased rates of acceleration are necessary. As the station-to-station distances are short, such schedule speeds can only be obtained by braking from relatively high speeds, which results in a large consumption of brake shoes and tyres, and increased maintenance costs due to penetration of iron dust into the electrical equipment.

As outlined in the previous chapters, standard equipment is accelerated by the cutting out in sequence of a series of resistance steps, resulting in a number of current peaks which give mechanical impulses to the train. With high rates of acceleration these impulses become undesirable due to the tendency to set up wheel-slip when working close to the maximum possible adhesion, and the possibility of damage to the couplings, etc., to say nothing of the discomfort to the passengers.

The use of the metadyne principle incorporates the features of eliminating sudden changes in the rate of acceleration, and also makes possible regenerative braking to a standstill.

PRINCIPLE OF THE METADYNE

Consider a normal two pole wave wound direct current machine armature, being rotated in a stator having four polar projections. Flux Φ_1 is set up by a current I_1 flowing in the circuit between the brushes "a" and "c". The resultant flux axis is indicated by the arrow (Fig. 173), the commutating axis lying on the positions "a" and "c" (the diagram being purely conventional does not allow for the step-in end windings). Due to the rotation of the armature in this flux, e.m.fs. are induced in the armature conductors, the voltage being a maximum at points "b" and "d". In the case where a pair of brushes are introduced at these points (Fig. 174) and connected to an external circuit, the current I_2, which then flows through the armature, sets up a flux Φ_2 acting perpendicular to Φ_1 in proportion to the current flowing. This in turn sets up a back e.m.f. at the primary brushes "a" and "c" which is also proportional to the secondary current I_2.

On connecting the primary circuit to a constant voltage supply, the two basic principles of a metadyne are apparent as follows:

(*a*) Current will flow from the line at such a value as to build up sufficient e.m.f. across the secondary load circuit for the back e.m.f. in the primary, due to this secondary current, to oppose the supply voltage, and in consequence this secondary current will remain constant irrespective of variations in the back e.m.f. of the load.

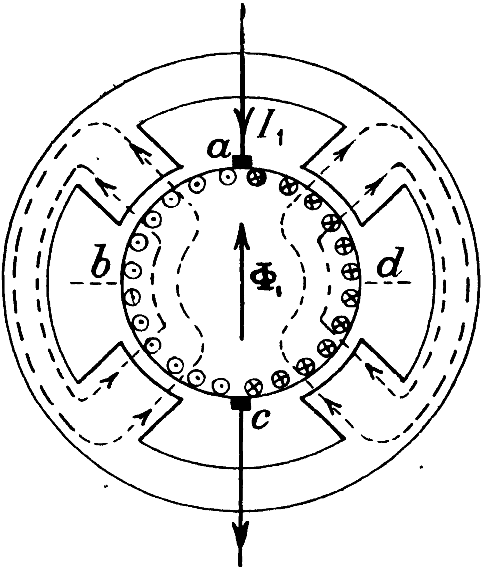


FIG. 173.—METADYNE PRIMARY FLUXES

(*b*) The electrical input and output of such an arrangement will be approximately equal, in that the machine will be kept running with a small driving current, hence the machine has the property of a direct current transformer converting power at constant voltage to power at constant current.

By the use of windings on directly opposite polar projections, variations in the output characteristic may be obtained. These windings are known as the "variators". One gives excitation on the primary flux axis, its effect being to either assist or reduce the primary armature flux, and a similar excitation on the secondary axis has the same effect on the secondary flux. For example the application of assisting ampere-turns on the primary variator will have no effect on the secondary output, but, due to the additional primary flux produced, a corresponding reduction in the input current will take place. This means that mechanical power must be supplied to the metadyne through its armature shaft to avoid retardation, and consequently the machine becomes a metadyne generator supplying power at constant current. Similarly a secondary variator excitation enables the output current to be controlled.

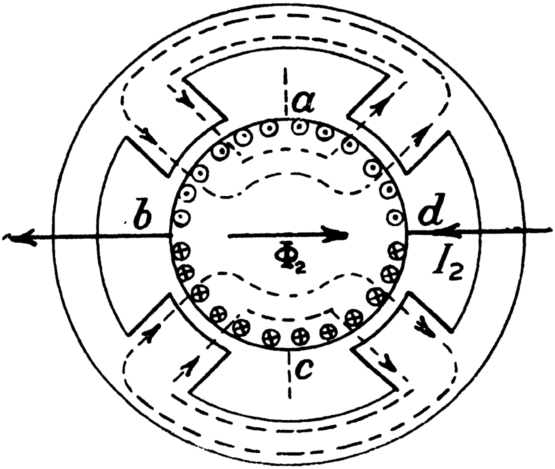


FIG. 174.—METADYNE SECONDARY FLUXES

REGULATOR WINDINGS

To ensure that the machine will continue to function as a metadyne transformer whilst using the secondary variator winding control, it is necessary to use a primary variator in order that the input torque shall be approximately equal to the output and the driving torque remain small. A "regulator winding" is used for this purpose, and is connected in series with the armature of a small "regulator motor" coupled to the metadyne shaft and supplied from the line (Fig. 175).

Should the speed of the metadyne tend to fall due to load or other reasons, this regulator motor being of the shunt-excited type will immediately take a large current from the line in an

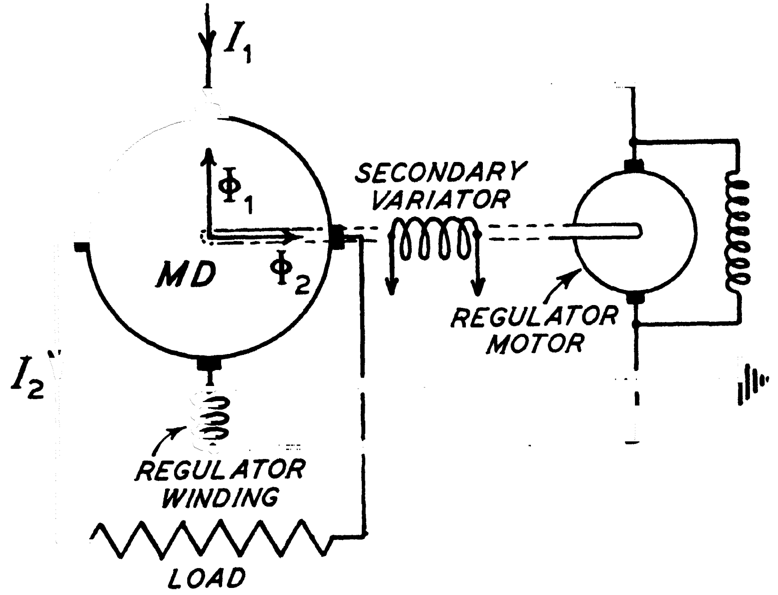


FIG. 175.—USE OF REGULATOR MOTOR AND WINDING TO OBTAIN SPEED STABILITY

attempt to maintain the speed. This current, flowing in the regulator winding, has the effect of reducing the primary flux, and in consequence the primary current increases thereby supplying the additional power required to prevent any further drop in speed of the metadyne. Inversely any tendency on the part of the metadyne to rise in speed has the effect of reducing the input current.

STABILITY WINDINGS

To prevent any tendency of the currents to oscillate, and in order to limit surges of current caused by rapid changes in line voltage, stability windings must be provided in both the primary and secondary circuits. These windings are in series with their respective circuits, and of course modify the characteristics of the metadyne. The effect of a primary stability winding is similar to that of a secondary variator winding, in that it causes an increase or decrease of the output current corresponding to the variations of the primary current. A secondary stability winding has no effect on the output characteristic but modifies the primary current with a resulting modification of the regulator current.

THE EIGHT CONNECTION

When it is possible to split the load supplied by a metadyne into two equal parts, the method of connection shown in Fig. 176a is employed, the load being fed from the line in series with the secondary circuit of the metadyne. With the voltage on the metadyne secondary varying from + Vs to — Vs, the total load voltage changes between zero and a value equal to twice the supply voltage Vs.

For regenerative braking, the "eight" connection makes it uneconomical for the load voltage to be reversed, and it is customary to re-connect the motors for braking as shown in Fig. 176b. The metadyne will then control the feeding back of current to the line, in exactly the same way as it controls current flowing from the line in the motoring connection.

In its simplest form, the metadyne is a source of constant current, automatically giving sufficient e.m.f. to maintain the current constant as the back e.m.f. of the load varies. For traction purposes it is simple to arrange the variator excitation so that the secondary (or output) current supplied to the motors varies as a function of their back e.m.f. and hence their speed. This is accomplished by the use of an exciting machine coupled to the metadyne, with its output controlled by field regulation according to the voltage across the load.

As both the variator field of the metadyne and the separately excited fields of the traction motors are connected in series and supplied from the exciter, it follows that as the motor current rises and falls under the control of the variator, simultaneous

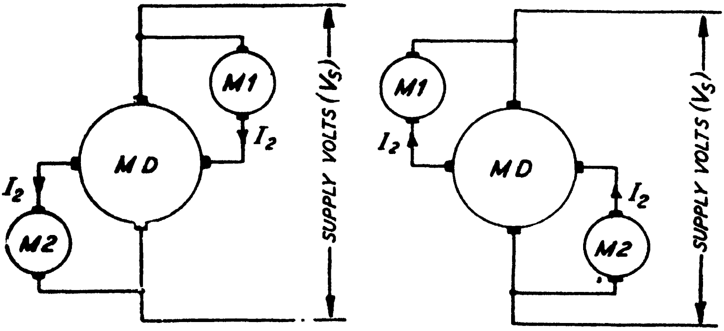


FIG. 176 (*a*).—THE "EIGHT" CONNECTION—MOTORING
(*b*).—THE "EIGHT" CONNECTION—BRAKING

strengthening and weakening of the traction motor fields will occur. This system ensures approximately corresponding values of field strengths and armature currents on the traction motors over the whole range of operation.

In addition to the fields which are separately excited from the exciter, the motors have small series windings in order to balance their respective load currents. This is desirable, as in effect all the traction motors are working in parallel.

In order that the metadyne and its traction motors can be connected to the line without producing violent surges of current, the metadyne must be running at its normal speed, and e.m.fs. must be present between the primary "a–c" and between the secondary "b–d" brushes, the sense of the latter being dependent on whether the motoring or generating function is required. This operation of connecting to the line is known as "entry", and is achieved by temporary reversal of the variator winding excitation, this being supplied either from the line or from the exciter.

TYPICAL METADYNE TRACTION EQUIPMENT

The following is a description of the two-coach units fitted for multiple-unit operation as supplied by The Metropolitan-Vickers Electrical Co. Ltd. for use on the London Passenger Transport Boards' electrified lines and illustrated in Fig. 177.

All the equipment is mounted on the underframe of the two cars which form the unit, one car carrying two traction motors, the metadyne and switch gear, and the second car two traction motors, the reverser, motor-generator set and compressor.

Bogies having the driving wheels nearer to the bolster than the trailing wheels are used to increase the adhesion on the motor axles, and due to the employment of these, it is necessary to have two motors on each car instead of the more conventional arrangement of a motor-coach and a driving trailer. Certain power cables must pass between the cars, these being shown on the schematic diagram as a curved line.

The metadyne consists of an armature with a two-pole winding, a commutator and four brush-arms, mounted in a four-pole frame, each pole carrying variator, regulator and stabilising windings. In addition there are four interpoles, two connected in the primary circuit and two in the secondary.

The exciter is a four-pole voltage generator with a wave wound armature. In order to obtain the special speed-acceleration

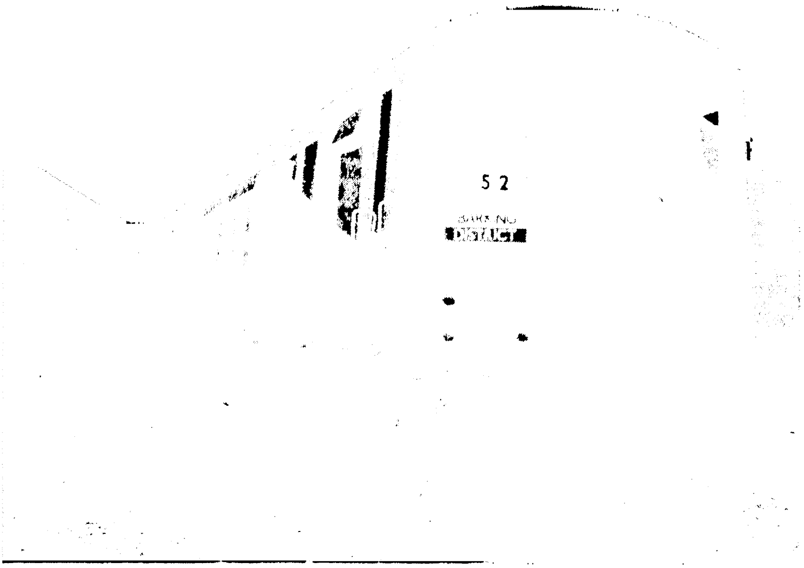


FIG. 177.—TWO-CAR METADYNE TRAIN

(*L.P.T.B. and Metro-Vickers*

characteristic, two of the poles are more saturated than the other two, and each pair is excited from different segments of the metadyne.

The regulator machine is provided with a shunt winding and two series windings. One of the two latter has a larger number of turns than the other, is used for starting the set, and as a stabilising winding when the metadyne is being driven light. On load this winding is cut out and the smaller winding used for compounding when the regulator machine is generating.

Fig. 178 shows the complete metadyne unit ready for mounting on the coach underframe.

METHOD OF OPERATION

Fig. 179 shows the main power schematic diagram and power chart, from which it will be seen that the equipment consists of a metadyne, regulator and exciter with their associated switchgear for controlling the four traction motors.

To start the metadyne running, contactors *CB*, *R*1, *R*3 are closed. This connects the regulator motor to the supply with a resistance in series with its armature. As the set speeds up, relays *S/L*1 and *S/L*2 function to close *R*1 contactor at a predetermined speed, and once this point has been reached, the equipment can be "entered" on to the line. When the master controller is moved to a running position, *EM*, *E* and *LS*2 close, providing that the reverser and motoring-regenerating changeover switch groups are correctly positioned. This excites the variator winding *VW* in the reverse direction, causing it to generate line potential across the "a–c" brushes. *R*5 contactor is then closed which strengthens up the shunt field of the regulator, and immediately following this *R*4, *LS*3, *LS*1 are closed simultaneously and R3 is opened. The operation of *R*3 and *R*4 contactors switches in the regulating field *RW* of the metadyne and the compensating field *RF* 3 of the regulator, at the same time cutting out the regulator series field *RF*2. This brings the metadyne under the speed control of its regulator winding and the regulator machine. The closing of *LS*3 contactor reverses the variator excitation, at the same time exciting the separately excited fields of the traction motors, and when *LS*1 closes, the whole equipment is brought on to the line. The entry in motoring is then completed by the opening of the contactors *EM* and *E*.

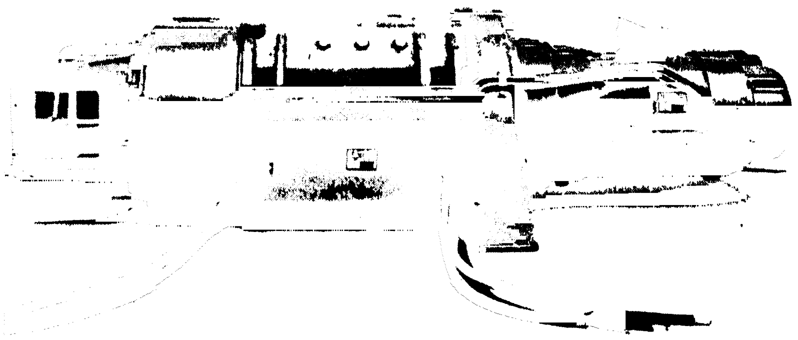
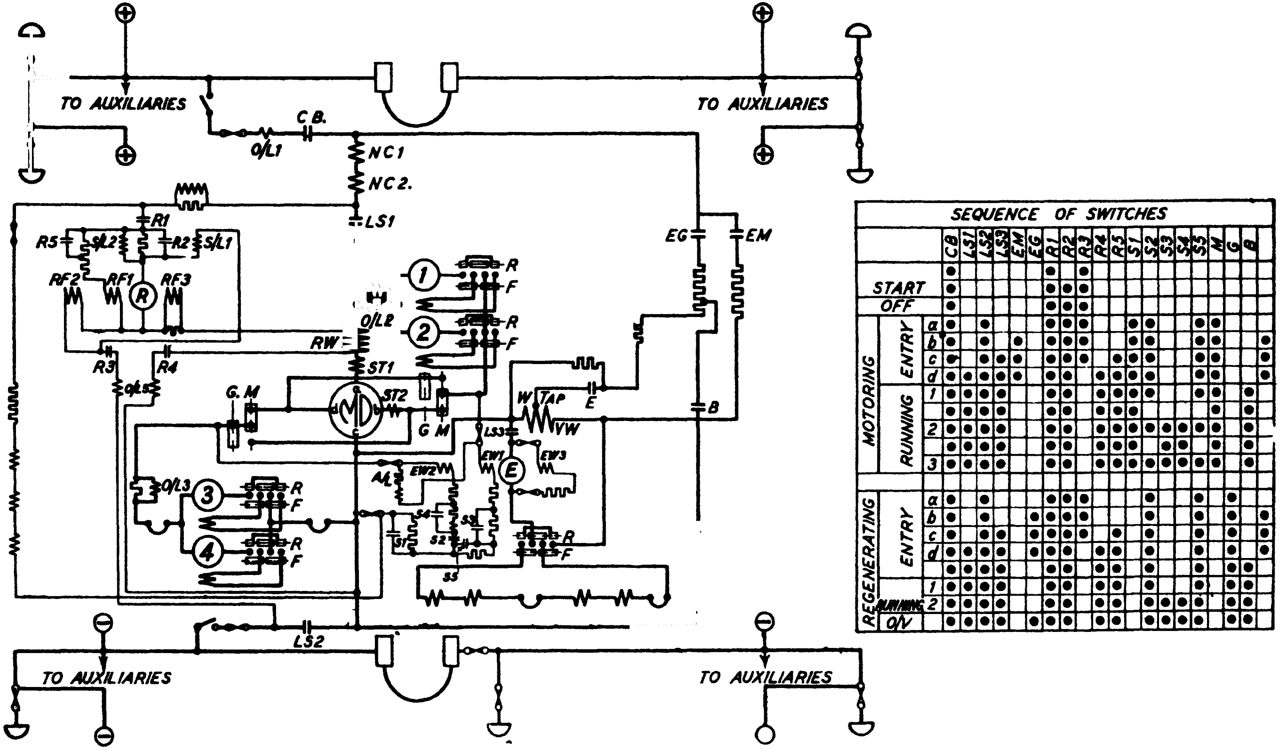


FIG. 178.—COMPLETE METADYNE SET

(*Metro-Vickers*)

In regeneration a similar method of entry is adopted, except that before any action takes place, the drum switch group is



SEQUENCE OF SWITCHES			CB	LS1	LS2	LS3	EM	EG	R1	R2	R3	R4	R5	S1	S2	S3	S4	S5	M	G	B	
			●						●		●											
START			●						●	●	●											
OFF			●						●	●	●											
MOTORING	ENTRY	a	●		●				●	●	●			●	●			●	●			
		b	●		●		●		●	●	●			●	●			●	●			●
		c	●		●	●	●		●	●	●		●	●	●			●	●			●
		d	●	●	●	●	●		●	●		●	●	●	●			●	●			●
	RUNNING	1	●	●	●	●			●	●		●	●	●	●			●	●		●	
			●	●	●	●			●	●		●	●	●					●		●	
		2	●	●	●	●			●	●		●	●	●	●	●	●	●	●		●	
			●	●	●	●			●	●		●	●	●		●	●		●		●	
		3	●	●	●	●			●	●		●	●	●	●	●	●	●	●		●	
REGENERATING	ENTRY	a	●		●				●	●	●				●			●		●		
		b	●		●			●	●	●	●				●			●		●		●
		c	●		●	●		●	●	●	●		●		●			●		●		●
		d	●	●	●	●		●	●	●		●	●		●			●		●		●
			●	●	●	●			●	●		●	●		●			●		●	●	
	RUNNING	1	●	●	●	●			●	●		●	●		●			●		●	●	
		2	●	●	●	●			●	●		●	●		●	●	●	●		●	●	
	O/V		●	●	●	●		●	●	●		●	●		●	●	●	●		●	●	

FIG. 179.—POWER CIRCUITS—METADYNE CONTROL

(*Metro-Vickers Gazette*)

changed over from motoring to regenerating. Contactor *EG* is then closed in place of *EM*, after which entry proceeds as for motoring.

After entry is completed *B* contactor is closed. When regenerating, if the line is unreceptive, the voltage delivered by the metadyne will rise, and after this reaches a predetermined value, the over-voltage relay operates to close *EG* which connects a portion of the regenerative entry resistance across the line for braking purposes. If after this sequence has occurred, the voltage continues to rise, the metadyne is cut off the line. To prevent reverse rotation of the motors when coming to a stop in regeneration, the no-current relay *NC*1 cuts the metadyne off the line at a small value of regenerated current, leaving the normal air brake to bring the train finally to rest.

It will be noted that the exciter has three fields *EW*1, *EW*2 and *EW*3. In the motoring connection *EW*1, wound on one pair of poles of the exciter, is connected across the metadyne brushes "c–b", and consequently provides a falling excitation with rising motor speed. *EW*2, wound on the other pair of poles of the exciter, is connected across the metadyne brushes "c–d", and consequently provides a rising excitation with motor speed. *EW*3 is shunt connected. The combined effect of these fields relative to the motor speed provides a characteristic rising quickly to a maximum, and then falling away as the traction motor voltage approaches 600 volts. This has the effect of producing high acceleration during starting and limiting the balancing speed to a desired value.

In the regenerating position, exciter fields *EW*1 and *EW*2 have their connections interchanged to metadyne brushes "c–d" and "c–b" respectively, so giving a characteristic of such a form that as the speed falls, the braking effort rises to a maximum at about 12 to 15 m.p.h., and then falls off rapidly with further reductions in speed.

The controller is provided with three notches in motoring and two in regeneration, and operates the small contactors *S*1 to *S*5 which control the exciter field resistance, and hence the value of excitation. To limit the balancing speed of the train over short distances, the relay *A*/*L* is employed on the first two motoring notches.

Metadyne traction equipment in general should be regarded as supplementary to the standard rheostatic type and not as superceding it. For an equivalent duty the standard rheostatic equipment is lighter in weight and costs less than the metadyne equipment, so that where the advantages of regeneration, acceleration and smoothness of operation are not important, the additional capital outlay will not be justified. While the efficiency of starting with metadyne equipment is higher than that of the rheostatic type, the efficiency during running is lower due to the metadyne losses which are going on continuously, so that there must come a time when the decrease in energy consumption due to efficiency in acceleration and the credit of regeneration, is offset by the losses during the standstill, free running and coasting periods.

FUTURE POSSIBILITIES IN THE FIELD OF ELECTRIC TRACTION

The possibilities in the field of electric traction, both road and rail, are immense.

The advantages of trolley-bus services, already well known for passenger carrying capacity, are quite likely to be improved by the introduction of the automatic acceleration feature to reduce the running time required over each route. This will enable an increased service frequency to be operated with the same number of vehicles as at present, or will enable the normal service to be operated with a reduced number. Further, manufacturers are pressing for an increase of 6 inches to make the maximum width 8 ft., in order to allow a wider gangway and improved seating arrangements. Many vehicles of this width originally built for overseas export, have been placed in service in this country since 1939.

In the railway traction field various schemes are in their experimental stages for control of traction motors without the use of starting resistances, mostly working on the line voltage "buck" and "boost" principle, some incorporating the constant current accelerating feature.

A new locomotive has recently been introduced on the Southern Railway for mixed traffic work, and incorporates an interesting feature in that it can continue to exert a tractive effort after all its collector shoes have left contact with the live rail, such as when crossing gaps in the latter or running into dead sections. Details of the system employed have not yet been made public.

Several areas exist in this country which merit investigation into the possibilities of electrifying the suburban traffic due to the relief of congestion so obtained. An example of a decision to electrify suburban services to reduce congestion, is that of the L.N.E.R. electrification out of Liverpool Street, at present held up due to the war. At peak periods the traffic density on this section is one of the heaviest in the world.

The possibility of general main-line electrification in this country at present is somewhat remote, as there are not many districts where the advantages obtained would merit the expenditure. However, in certain areas, where heavy freight traffic is encountered, electric haulage would probably prove advantageous. In the diesel-electric field, considerable opportunities exist for long distance main-line traffic as well as for freight and shunting work.

One outstanding advantage which would result from complete conversion to electric or diesel-electric locomotive haulage, is that a small number of standardised types of locomotives would be necessary, and also, due to the increased availability and fuel capacity in the case of diesel-electric locomotives, a considerable reduction in the locomotive stock would be possible.

In conclusion, it is the authors' opinion that, in the next few years considerable development in the field of electric and diesel-electric traction will take place, both in this country and overseas, due in many cases to the large amount of reconstruction work and locomotive replacement which is now necessary.

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